STATE OF DELAWARE
UNIVERSITY OF DELAWARE

DELAWARE GEOLOGICAL SURVEY

Robert R. Jordan, State Geologist

BULLETIN NO. 16

GROUND-WATER RESOURCES OF THE PINEY POINT AND CHESWOLD AQUIFERS IN CENTRAL DELAWARE AS DETERMINED BY A FLOW MODEL

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PREPARED BY THE UNITED STATES GEOLOGICAL SURVEY
IN COOPERATION WITH THE
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FOREWORD

This report is part of an effort that was begun in 1974 to characterize and study major aquifers in Delaware by digital (computer) models. The two reports resulting from this cooperative effort with the U. S. Geological Survey have each advanced our knowledge of the State's ground-water resources and also contributed to the advancement of ground-water modeling techniques. Indeed, the computer model resulting from the research described herein represents the "state-of-the-art" in this highly technical and rapidly changing field.

The use of computer models allows analyses of highly complex hydrologic data that improve our understanding of aquifers and aquifer systems. In addition, models permit evaluations to be made of hypothetical pumping schemes by synthesizing their effects. Such massive manipulation of data would be nearly impossible without the availability of modern computers.

Digital models greatly increase our abilities to plan for future water needs. However, extreme care is necessary in the use of models as predictive tools. Several years of effort are usually required to complete a model comparable to the one described in this report. The model inherently reflects the skills and intentions of the author and the capabilities of the available computing equipment. Models have limitations and can produce misleading results if they are abused. Thorough knowledge of the operating assumptions and of the quality and density of input data are necessary in order to use a model within the constraints intended by the modeler.

This report contains the essence of the model produced by the studies recorded herein. The total model includes the documentation of the data, operating precepts, and instructions given the computer; it is not a mechanical device standing by to answer all questions on command. Moreover, models tend either to become outdated or to require expensive "maintenance." Therefore, they are generally utilized for a single, controlled research effort and then retired. The model has permanency, however, in the sense that its techniques contribute to the next generation of improved models.

The initial report documenting a new model and its results is, by nature, quite technical and may contain details of interest only to other specialists. The present report is no exception as it faithfully details the data bases and the assumptions made by the author. A less technical summary report emphasizing the applications of the results of this work in water-supply planning is to be published as a companion document.

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GROUND-WATER RESOURCES OF THE PINEY POINT AND CHESWOLD AQUIFERS IN CENTRAL DELAWARE AS DETERMINED BY A FLOW MODEL

ABSTRACT

A quasi three-dimensional model was constructed to simulate the response of the Piney Point and Cheswold aquifers underlying Kent County, Delaware to ground-water withdrawals. The model included the Magothy, Piney Point, Cheswold, and unconfined aquifers, and was calibrated using historical pumpage and water-level data. Model calibration was accomplished through the use of both steady-state and transient-state simulations.

The aquifer system was assumed to be in equilibrium with a pumpage of 2.2 million gallons per day (Mgal/d) prior to the early 1950's. A steady-state simulation of this condition was used to refine estimates of (1) transmissivities of the Cheswold and Piney Point aquifers, and (2) vertical hydraulic conductivities of confining beds above and below the Cheswold aquifer. The transient-state simulation involved the changes in pumpage that occurred from 1952 to 1977 and was used to (1) refine estimates of the values of storage coefficients and specific storages of the aquifers and confining beds, and (2) further refine hydraulic properties used in the steady-state simulation. Calibration involved comparison of (1) simulated and observed head declines for both steady-state and transient-state simulations, and (2) computed and observed hydrographs at 17 observation wells for the transient-state simulation.

Calibration of the model showed that (1) transmissivity of the Cheswold aquifer ranges from 7,400 feet squared per day (ft^2/d) to less than 1,000 ft^2/d in the Dover area and (2) vertical hydraulic conductivity of the confining bed separating the Cheswold and unconfined aquifers ranges from 4.0×10^{-4} feet per day (ft/d) to 1.2×10^{-3} ft/d. Transmissivity of the Piney Point aquifer ranges from 7,350 ft^2/d to effectively zero at the boundaries of the aquifer, and the vertical hydraulic conductivity of the confining bed separating the Piney Point and Cheswold aquifers is 2.0×10^{-5} ft/d. The model study indicates that substantial vertical leakage from the overlying unconfined aquifer into the Cheswold aquifer is occurring in an area northwest of Dover.

The calibrated multilayer model was used to evaluate long-term water-level declines that would result from projected increases in withdrawals from both the Piney Point and Cheswold aquifers. Various withdrawals were simulated; the largest was 16.6 Mgal/d or almost double the 1977 pumpage. This withdrawal produced maximum water-level declines of 162.5 feet and 75.7 feet in the Piney Point and Cheswold aquifers, respectively, below the 1977 potentiometric surfaces. These projected water levels are above the tops of the aquifers.

INTRODUCTION

General Statement

The Delmarva Peninsula is a part of the Atlantic Coastal Plain that extends from Long Island, New York, southward to about southern Georgia. The peninsula is underlain by unconsolidated marine and nonmarine deposits consisting of clay, silt, sand, and gravel. The sediments range in age from at least Early Cretaceous to Holocene and lie unconformably on a crystalline-rock basement. In Kent County, Delaware the principal water-bearing units of the Coastal Plain are sands of the Magothy and Piney Point Formations, the Cheswold aquifer of the Chesapeake Group, and overlying unconfined aquifers--principally sands of the Columbia Group. In the discussions to follow, the term "aquifer" refers to the sandy and water-bearing portions of the Magothy and Piney Point Formations. In most cases, the terms "formation" and "aquifer" are not equivalent.

The Piney Point and Cheswold aquifers are highly stressed and provide a large percentage of the water used in Kent County. The water supplies of the City of Dover, Town of Camden-Wyoming, Dover Air Force Base, and a number of large industries in Kent County are provided by wells screened in these aquifers. Although the first wells tapping the Piney Point and Cheswold aquifers were drilled in the late 1880's, substantial development of these aquifers did not begin until the 1950's and 1960's, respectively. Pumpage has resulted in declining water levels in both the Piney Point and Cheswold aquifers in the Dover area. Drawdowns of approximately 130 feet have been observed in the Piney Point aquifer at Dover Air Force Base for the 25-year period 1952-77. Similarly, water levels in the Cheswold aquifer at Dover have declined as much as 60 feet during the same period.

Purpose and Scope

The dependence of Kent County on the Piney Point and Cheswold aquifers as a water resource, and the decline in water levels in both aquifers during the past 25 years indicate the need for a thorough understanding of these aquifer systems. Therefore, the objectives of this study are to:

1. Define the hydraulic properties of the Piney Point and Cheswold aquifers and adjacent confining beds.

2. Construct and calibrate a multilayer model of the Piney Point and Cheswold aquifers and compare this model with the results of earlier model studies.

3. Use the calibrated model to evaluate the long-term effects of hypothetical withdrawals on the aquifer being pumped (Piney Point or Cheswold aquifer) and on any other aquifer in the system.

The location of the study area [230 square miles (mi^2) in Kent County, Delaware] is shown in Figure 1. The area is only a small portion of the total area modeled. The model (Figure 2) covers an area of about 2,370 mi^2 and includes

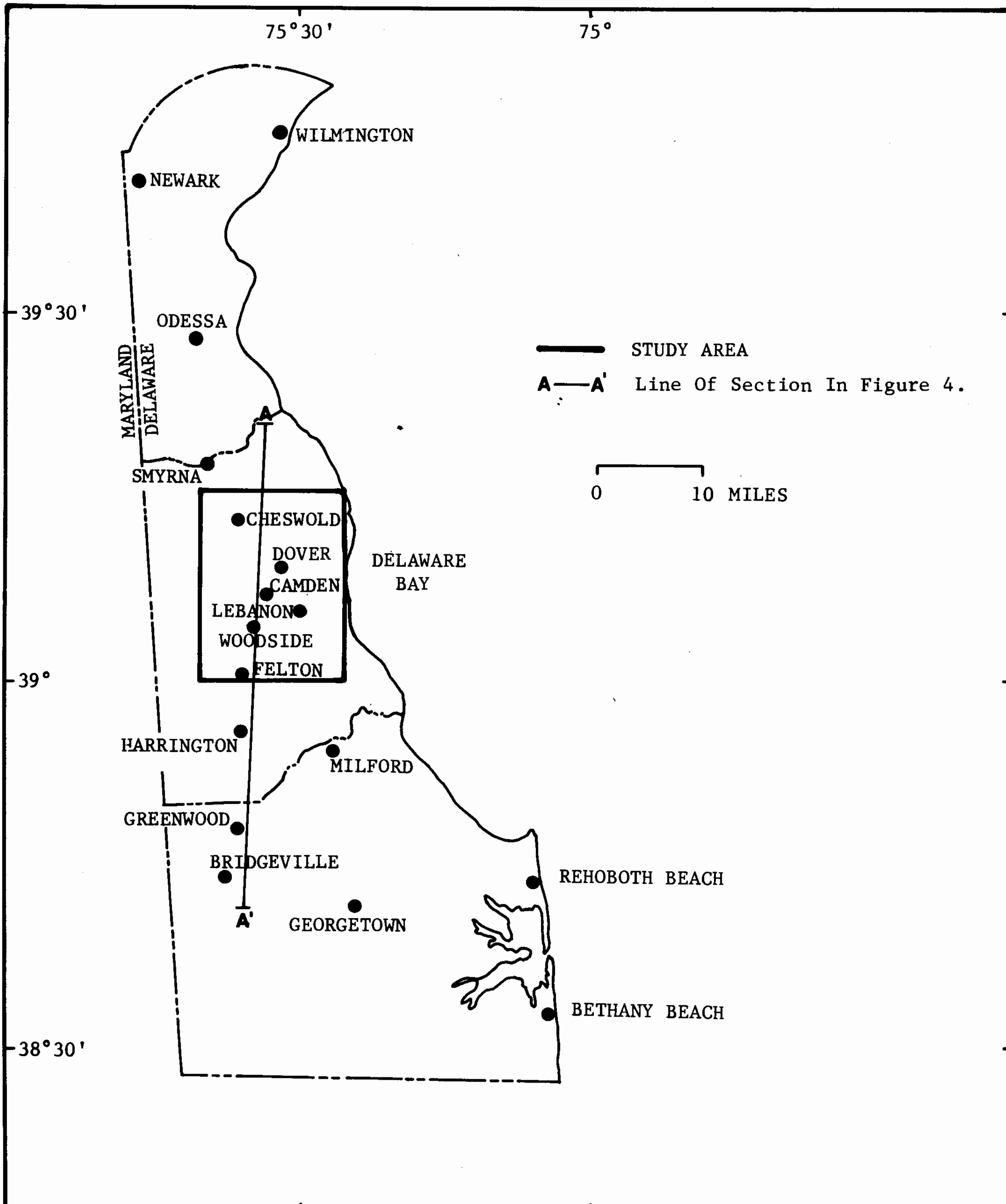


FIGURE 1 - LOCATION OF STUDY AREA.

most of the Delmarva Peninsula, Delaware Bay, and a small part of southern New Jersey. The model is bounded on the north by the subcrop of the Cheswold aquifer and on the south by a southeasterly trending line representing the downdip limit of the Piney Point aquifer. To the northeast, in southern New Jersey, the model is bounded by the Cheswold aquifer subcrop (considered to be part of the Kirkwood Formation) and on the southwest by a southeast-trending line running from Easton, Maryland, to the Nanticoke River at Vienna, Maryland. The model uses a fine grid spacing to produce detailed results in the study area, as shown in Figures 2 and 3.

Because flow occurs between aquifers, the model is designed to simulate the response of a multiaquifer system. In the vertical direction the model includes the unconfined, Cheswold, Piney Point, and Magothy aquifers in addition to the confining beds which separate these aquifers.

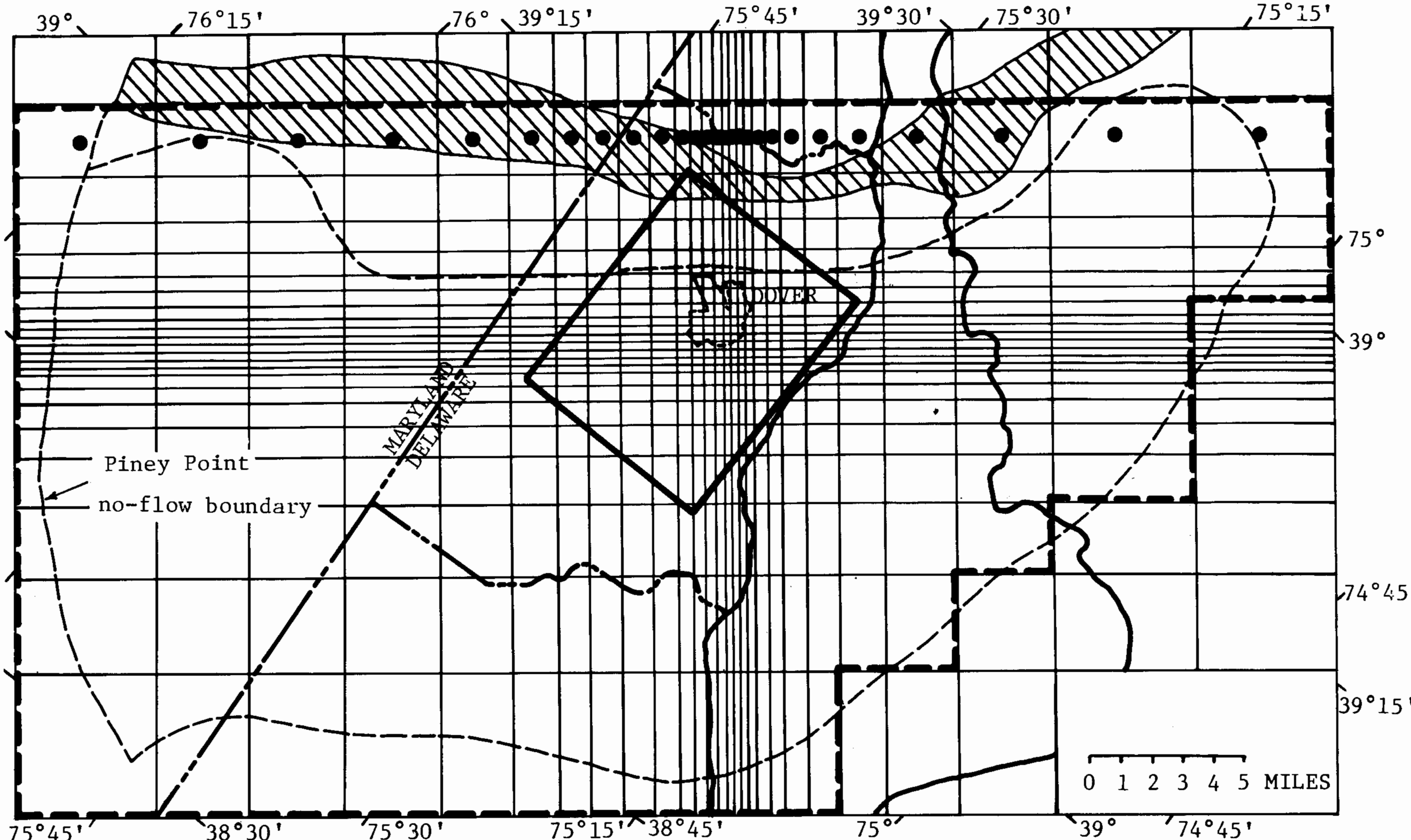
Acknowledgments

This study was made by the U. S. Geological Survey in cooperation with the Delaware Geological Survey, and through contributions by the City of Dover, the Delaware Department of Natural Resources and Environmental Control, and Kent County.

Robert R. Jordan, State Geologist and Director of the Delaware Geological Survey, provided assistance throughout the study. In addition, Kenneth D. Woodruff, Associate Director, and John H. Talley, Hydrogeologist, both of the Delaware Geological Survey, geophysically logged several boreholes in Kent County.

Jack R. Woods, Director of Public Works of the City of Dover, and his staff supplied water-level and pumpage data in the Dover area. Michael A. Apgar and Paul M. Williams of the Delaware Department of Natural Resources and Environmental Control, supplied information on wells constructed during the study.

The writer also wishes to thank Walter L. Fritz, Kent County Engineer, for his scenarios of future development of water supplies in Kent County. Finally, thanks are given to the staff of the University of Delaware Computing Center, who assisted the writer in compiling and executing the digital model. This report is also a portion of a doctoral dissertation submitted by the author to the faculty of Rensselaer Polytechnic Institute, Troy, New York.



Finite-difference block

Simulated no-flow aquifer boundary

Area of high effective vertical hydraulic conductivity of the confining bed separating the Cheswold and unconfined aquifers

Constant head node representing Cheswold aquifer subcrops

Approximate location of Cheswold aquifer subcrop

FIGURE 2 - LOCATION OF MODEL GRID, HYDROLOGIC BOUNDARIES, AND STUDY AREA.

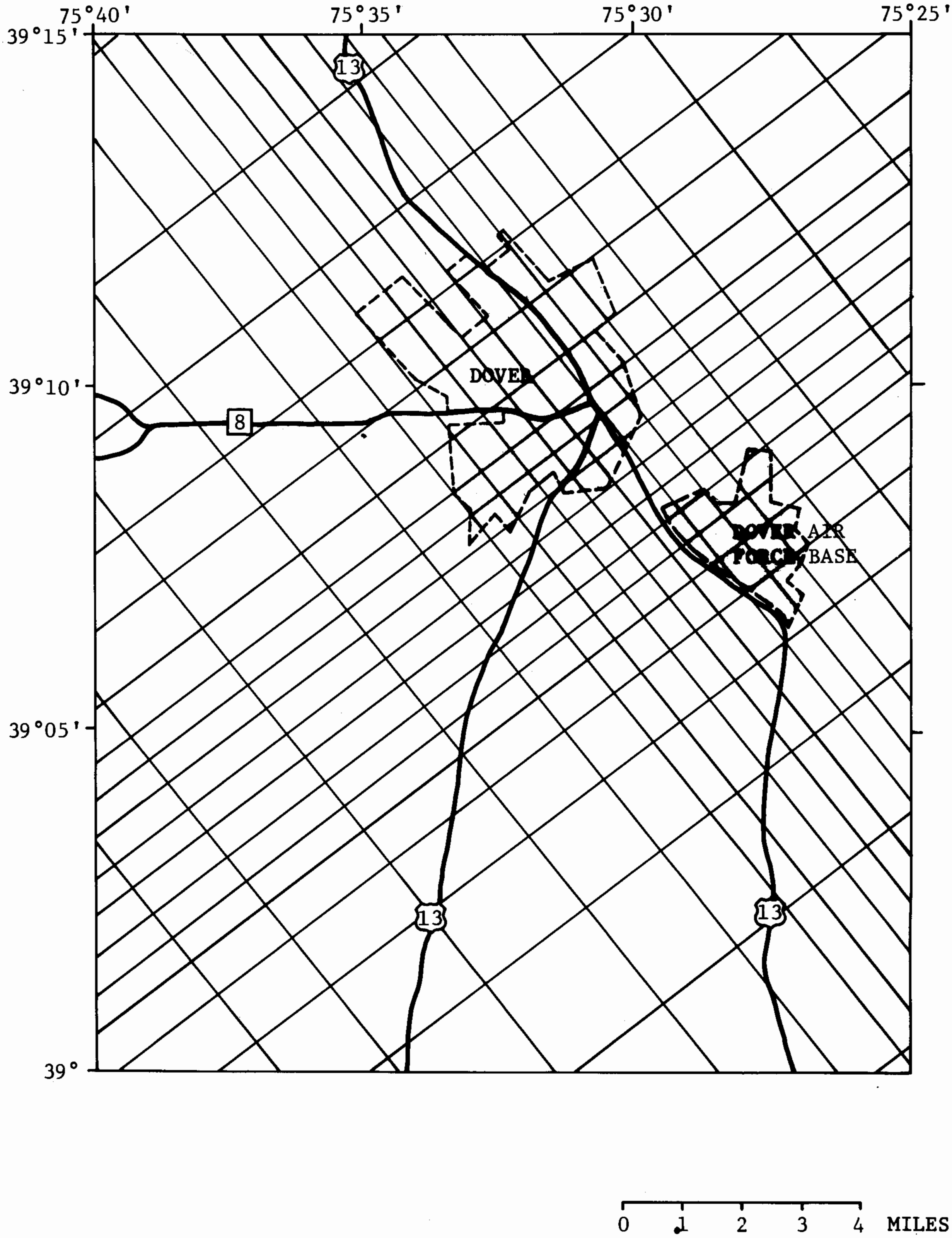


FIGURE 3 - LOCATION OF THE MODEL GRID IN THE STUDY AREA.

GEOLOGIC AND HYDROLOGIC FRAMEWORK

Coastal Plain sediments in the Delmarva Peninsula occur as a seaward-thickening wedge of sand, silt, and clay. Cushing, Kantrowitz, and Taylor (1973) reported that the unconsolidated sediments range in thickness from zero at the Fall Line to more than 8,000 feet along the coast in Maryland. The Coastal Plain sediments have been divided into stratigraphic units as shown in Table 1.

In studying the movement of ground water, the sediments have been divided into two major, areally extensive, lithologic units that are defined (Lohman and others, 1972, p. 2, 5) as follows:

(1) An aquifer is a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells.

(2) A confining bed is defined as a body of impermeable material stratigraphically adjacent to one or more aquifers. Its hydraulic conductivity may range from nearly zero to some value distinctly lower than that of the aquifer.

Although many site-specific hydrologic studies have been completed for the Delmarva Peninsula, the study by Cushing, Kantrowitz, and Taylor (1973) was the first to map the 10 major aquifers underlying the peninsula (Table 1). Their maps show structural contours, thickness, and the lateral extent of the 10 major aquifers. The interested reader is referred to their report for detailed descriptions of the external and internal geometries of these major aquifers.

Many of the aquifers identified in Table 1 are absent or insignificant in the study area. The Rancocas, Pocomoke, and Manokin aquifers are absent. The Frederica and Federalsburg aquifers are thin (generally less than 35 feet) with low transmissivity and are considered as parts of the confining beds. The aquifers and confining beds included in this study are shown in the last column of Table 1.

Hydrogeology of the Aquifers

Lithologic Character

The Magothy Formation, the oldest (Upper Cretaceous) layer of sediments included in the model, represents a transition between marine and nonmarine deposition. Jordan (1962) described the Magothy as a white and buff quartz sand with beds of gray or black clayey silt. Few wells in the study area have penetrated the Magothy Formation because it occurs at depths in excess of 1,000 feet and users have been able to satisfy their needs at shallower depths. Rasmussen, Groot, and Depman (1958) reported the depth (below land surface) to the top of the Magothy Formation as 1,275 feet at Dover Air Force Base.

Table 1.--Stratigraphic units and major aquifers underlying the Coastal Plain of Delaware and Maryland.

System	Series	Stratigraphic Units: Maryland	Stratigraphic Units: Delaware	Aquifers in the Coastal Plain	Aquifers and confining beds in Kent County study area as used in this report
Quaternary	Holocene	---------	---------	Unconfined aquifer	Unconfined aquifer
	Pleistocene	Columbia Group undivided	Columbia Group undivided		
Tertiary	Miocene	Brandywine Formation	---------		
		Chesapeake Group: St. Marys Formation Choptank Formation Calvert Formation	Chesapeake Group undivided	Pocomoke aquifer Manokin aquifer Frederica aquifer Federalsburg aquifer Cheswold aquifer	Sandy confining bed Cheswold aquifer Silty confining bed
	Oligocene	(Section not present)	(Section not present)	(Section not present)	(Section not present)
	Eocene	Piney Point Formation Nanjemoy Formation	Piney Point Formation Nanjemoy Formation	Piney Point aquifer	Piney Point aquifer
	Paleocene	Aquia Formation Brightseat Formation	Rancocas Group: Vincentown Formation Hornerstown Formation	Rancocas aquifer	Clayey confining bed
Cretaceous	Upper Cretaceous	Monmouth Formation Matawan Formation Magothy Formation Raritan Formation	Mount Laurel Formation Matawan Group: Marshalltown Formation Englishtown Formation Merchantville Formation		
			Magothy Formation	Magothy aquifer	Magothy aquifer
	Lower Cretaceous	Potomac Group: Patapsco Formation Arundel Formation Patuxent Formation	Potomac Formation	Nonmarine Cretaceous aquifer	

Explanation: ▧ Section not present. (Modified from Cushing, Kantrowitz, and Taylor, 1973)

The stratigraphic nomenclature used is that of the Delaware Geological Survey and Maryland Geological Survey and does not necessarily follow the usage of the U. S. Geological Survey.

The Magothy aquifer occurs as the sandy portion of the Magothy Formation. Cushing, Kantrowitz, and Taylor (1973, Plate 3) reported the depth below sea level of the Magothy aquifer to be about 950 feet at Cheswold; 1,225 feet at Dover Air Force Base; 1,425 feet near Greenwood; and 1,510 feet near Bridgeville. In the study area, the aquifer averages about 100 feet in thickness and contains brackish water (Cushing, Kantrowitz, and Taylor, 1973, Plate 3; Kraft and Maisano, 1968).

The Piney Point Formation consists of marine sediments that are considered to be of Eocene age. Otton (1955) first identified the formation on the basis of data from a test well at Piney Point in southern Maryland. Rasmussen and Slaughter (1957) extended the use of the term "Piney Point Formation" to the late Eocene sediments of Maryland's Eastern Shore. Brown, Miller, and Swain (1972) examined sediments of the Piney Point type-section and found the formation to be of Claiborne (middle Eocene) age. Rasmussen, Groot, and Depman (1958) were able to recognize the Piney Point Formation in a test well at Dover Air Force Base, Delaware, on the basis of paleontology, lithology, and well logs. The formation at this location was considered to be Jacksonian (late Eocene) in age. However, Jordan (1962) pointed out that additional paleontological work suggested that much of the unit is middle Eocene in age. Talley (1975) also assigned an Eocene age to the Piney Point Formation in the Greenwood test well (Nc13-3). The location of this well and others referred to in the text are shown in Figure 4.

The Piney Point Formation contains green, fine to medium, glauconitic sand (Jordan, 1962). The occurrence of glauconite is useful in determining the contact between the Piney Point Formation and overlying non-glauconitic sediments of the Chesapeake Group. The southeast-dipping Piney Point Formation is largely restricted to an elongate-lenticular body of sediments trending roughly northeast-southwest (Figure 2). In central and southern Kent County, Talley (1975) determined the strike of the Piney Point Formation to be between N30°E and N47° E, with dips of 15 to 31 feet per mile (ft/mi) to the southeast. The maximum known thickness of the formation is 251 feet at Greenwood, Delaware. The thickness decreases to zero, both updip and downdip, and to the northeast and southwest along strike in New Jersey and Maryland.

The Piney Point aquifer occurs as the upper part of the Piney Point Formation in much of southern New Jersey. On the Delmarva Peninsula, however, the Piney Point aquifer consists of almost the entire thickness of the Piney Point Formation, except near the updip and downdip limits of the aquifer. The upper part of the aquifer appears to be the most productive as evidenced by geophysical logs which show the aquifer becoming progressively more silty with depth (Cushing, Kantrowitz, and Taylor, 1973). Updip, the aquifer becomes thinner and more silty, and pinches out north of Dover. Downdip, the Piney Point aquifer thins and becomes progressively more silty and clayey. It cannot be considered a productive aquifer much farther south than Greenwood or Milford, Delaware.

The Chesapeake Group (undivided), a wedge-shaped mass of sediments that thickens and dips in a southeasterly direction, attains a maximum thickness in Delaware of about 1,550 feet beneath Fenwick Island (Rasmussen, Wilkens, and Beall, 1960). The Chesapeake Group is of Miocene age and unconformably overlies the Piney Point Formation on Delmarva Peninsula. The Chesapeake Group consists of gray and bluish-gray silt containing beds of light gray, fine to medium sand

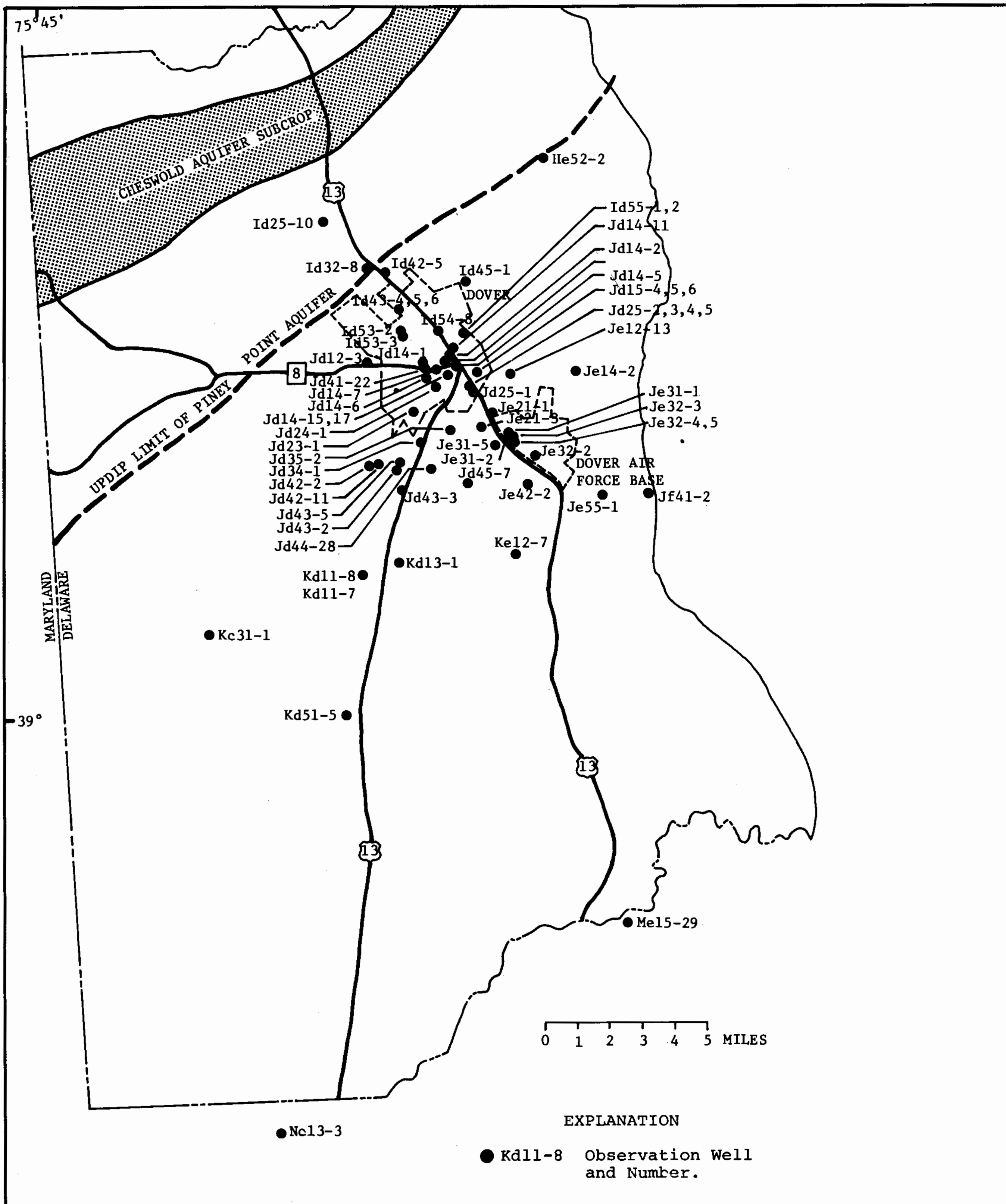


FIGURE 4 - LOCATION OF WELLS.

(Jordan, 1962). Shells and shell fragments are common in the unit. Sundstrom and Pickett (1968) pointed out that these sediments represent a series of sea-level transgressions and regressions. Several aquifers have been identified in the Chesapeake Group on the peninsula, most notably the Cheswold, Federalsburg, Frederica, Manokin, and Pocomoke aquifers (Table 1). Of these, only the Cheswold aquifer is a significant aquifer in the study area; the rest of the Chesapeake Group sediments are considered to be confining beds in this study.

The lower sandy zone of the Chesapeake Group is the Cheswold aquifer. The aquifer is composed of fine to coarse sand and shells. Its thickness ranges from zero at its updip limit to more than 150 feet downdip. The aquifer is 50 to 75 feet thick in the Dover area. The top of the Cheswold aquifer ranges in depth from about sea level in the Smyrna-Clayton area to about 360 feet below sea level near Milford, in southern Kent County (Sundstrom and Pickett, 1968). Marine and Rasmussen (1955) reported the dip of the aquifer to be about 11 feet per mile between Smyrna and Dover. The Cheswold aquifer directly underlies the unconfined aquifer in a narrow subcrop belt about 8 miles north of Dover (Johnston and Leahy, 1977, Figure 4).

The Columbia Group (or Formation) overlies the Chesapeake Group and consists of fine to coarse sand occurring as a southward-thickening wedge across central and southern Delaware (Johnston, 1973). The Columbia Group is of Pleistocene age, mostly fluviatile in origin, and forms the water-table aquifer in most of Delaware (Jordan, 1962, 1964; Jordan and Talley, 1976). In some locations, the Columbia Group may rest directly upon the subcrop of an underlying Miocene aquifer with the entire sequence functioning as the water-table aquifer (Johnston, 1977). The saturated thickness of the unconfined aquifer ranges from about 15 feet north of Dover to about 170 feet near Milton. In the Dover area, the saturated thickness ranges from 15 to 56 feet.

Figure 5 shows a generalized geologic cross-section to the base of the Magothy aquifer. The section indicates the aquifers and confining beds modeled.

Movement of Ground Water

Before pumping began, hydraulic equilibrium prevailed in the aquifer system underlying Kent County. Recharge to the unconfined aquifer resulted from frequent periods of precipitation, and discharge occurred as evapotranspiration, base flow to streams, and downward leakage to the underlying Cheswold aquifer.

Prior to pumping, the Cheswold aquifer was recharged directly from the unconfined aquifer in its subcrop area and by downward leakage from the unconfined aquifer through the sandy confining bed in inland areas. Discharge was by upward leakage in coastal areas through the confining bed to the unconfined aquifer. The Cheswold aquifer probably received a very small amount of water by upward flow from deeper aquifers near the Delaware Bay, and discharged a very small amount of water by downward leakage to deeper aquifers inland.

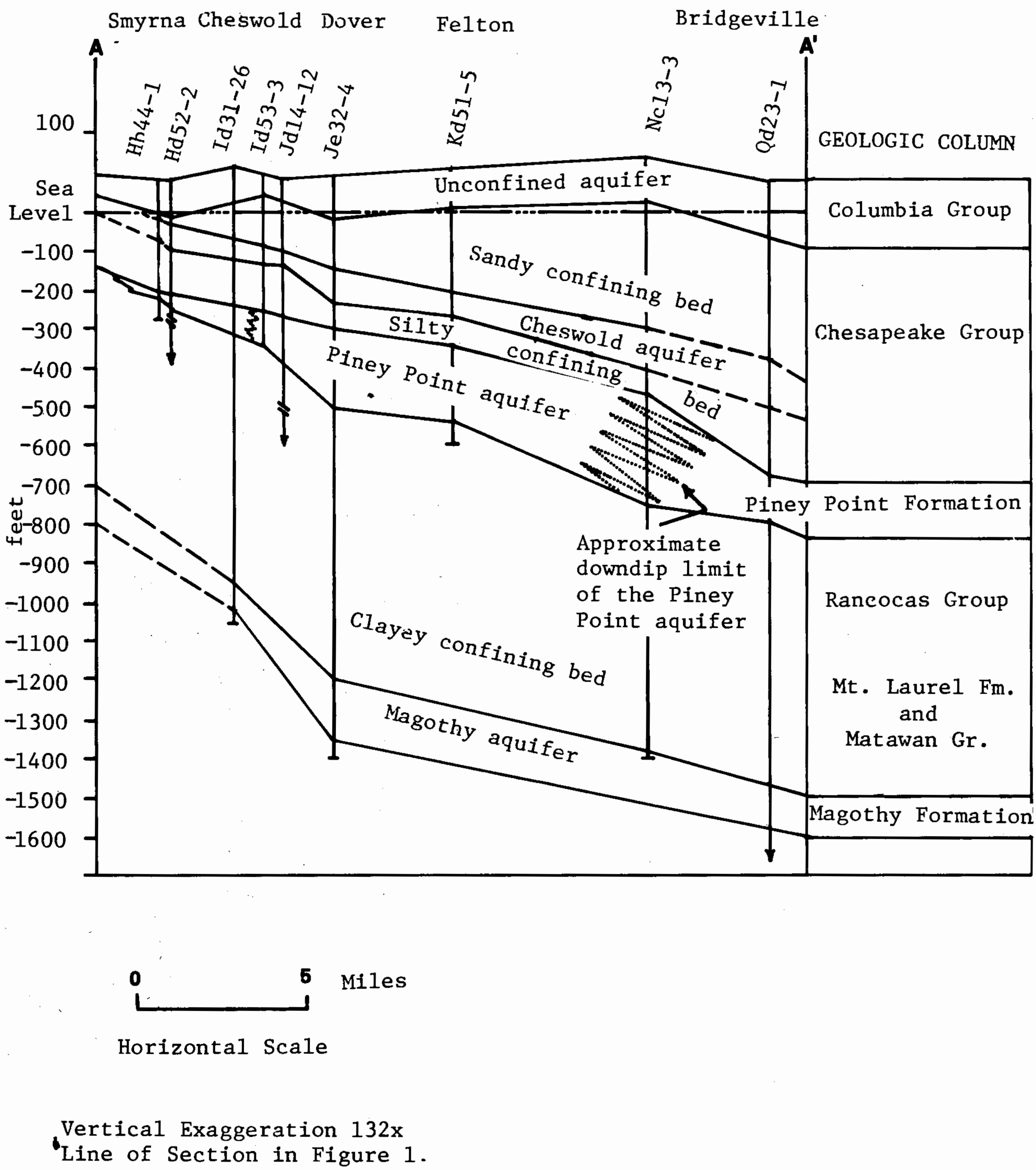


FIGURE 5 - GENERALIZED GEOLOGIC CROSS-SECTION FROM SMYRNA TO BRIDGEVILLE, DELAWARE.

The Piney Point aquifer neither crops out nor has a subcrop beneath an overlying aquifer, and all flow to and from the aquifer appears to be by vertical leakage through adjacent confining beds. Under prepumping conditions, the hydrology of the Piney Point aquifer involved recharge from overlying aquifers in updip areas, lateral movement through the aquifer, and discharge to overlying aquifers in downdip areas. The Piney Point aquifer probably also received extremely small amounts of water through upward leakage from the deeper Magothy aquifer.

The original hydrologic equilibrium within the Piney Point and Cheswold aquifers has been disturbed by the withdrawal of a large amount of water, causing two regional cones of depres ion to develop around Dover, Delaware. Pumping now accounts for a large part of the discharge from both aquifers within the study area. Water levels in the Piney Point and Cheswold aquifers have not stabilized in response to these pumping stresses, indicating that a new equilibrium has not been reached. Pumping has induced additional vertical leakage from the unconfined aquifer into underlying aquifers in the Dover area. This conclusion is supported by a reduction of approximately 30 percent or 10 cubic feet per second (ft^3/s) in the base flow of the St. Jones River near Dover (Johnston and Leahy, 1977).

If the present pumping scheme is maintained, the aquifers will eventually reach equilibrium. However, if future ground-water withdrawals increase in any aquifer of the system, additional time will be required for the aquifers to reach a new equilibrium.

Ground-Water Pumpage

The Piney Point and Cheswold aquifers provide approximately 80 percent of the total municipal and industrial water pumped in Kent County. Over 90 percent of the modeled pumpage from the Piney Point and Cheswold aquifers occurs within the study area. Significant pumpage from the Piney Point aquifer in the vicinity of Cambridge, Maryland, (located approximately 50 miles southwest of Dover) has occurred in the period 1952-77. However, water levels in the modeled area have not declined in response to these withdrawals (Williams, 1979, Plate 4). Therefore, the Cambridge, Maryland, pumpage was not included in the model.

The Magothy aquifer is essentially unpumped in Kent County because it is too deep and contains brackish water. Only one Magothy well located near Cheswold is being lightly pumped. Pumpage from the unconfined aquifer (Columbia Formation) in the study area is light and widely distributed, and no long-term decline in the water table has been observed (Johnston, 1977). Furthermore, this pumpage is used primarily for irrigation and domestic supply and most of the water is returned to the aquifer after use.

The Cheswold aquifer has been used continuously as a source of water at Dover since 1893. With the gradual addition of wells, withdrawals have increased from 0.05 million gallons per day (Mgal/d) in 1893, to 6 Mgal/d in 1973. Data on pumpage from the Cheswold aquifer are unavailable for the period 1893 to 1931. However, the literature suggests that the majority of the early development occurred before 1931. Eastman and Beckett (1931) reported a Cheswold aquifer withdrawal of 0.6 Mgal/d by the City of Dover in 1931. Marine and Rasmussen (1955) presented a brief summary of the development of the Cheswold aquifer by the City of Dover. In addition to the 1893 well, an 8-inch production well was drilled in 1900. In 1909, two more production wells were screened in the Cheswold aquifer. In 1932, well Jd14-2 (Delaware Geological Survey numbering system), which is still in use, was drilled at the old powerplant site on the St. Jones River. Other wells include Jd14-1 drilled at the Division Street site in 1938 and well Jd24-1 drilled at the Dover Street site in 1948. More recently, the following Cheswold aquifer production wells have been added to the city system: Jd14-6 at Water Street (1952); Jd15-2 at Bayard Avenue (1955); Jd15-4 at the East Dover Elementary School (1964); Jd25-2 at Danner Farm (1964); and Jd14-17 at the Water Treatment Plant (1978).

Several large industries rely on the Cheswold aquifer for water supply; among the largest are a latex manufacturing plant and a poultry dressing plant. Wells at the latex plant (Jd14-11, Jd15-1) were drilled in 1948 and 1953, and the well at the poultry processing plant (Jd14-5) was installed in 1931. Marine and Rasmussen (1955) estimated the 1953 pumpage from these wells to be 1.1 Mgal/d. An estimate of a pre-1952 industrial withdrawal in the Dover area was 0.6 Mgal/d. This estimate was obtained by subtracting the withdrawal of well Jd15-1 at the latex plant from the total 1953 industrial pumpage. The remaining early developers of the Cheswold aquifer are Dover Air Force Base and Delaware State College. Pumpage from wells at these sites in the 1940's was estimated to be 0.5 Mgal/d and 0.05 Mgal/d, respectively.

Although a decline in head of 23 feet was observed in the Dover area between 1939 and 1952 (Marine and Rasmussen, 1955), it appears that the majority of this decline probably occurred prior to the late 1940's. This is implied by the 1950-52 pumpage for the City of Dover reported by Marine and Rasmussen (1955). During this period, Cheswold aquifer pumpage by the City of Dover remained relatively constant at about 1.0 Mgal/d. Total Cheswold aquifer pumpage in the late 1940's and through 1951 has been estimated (Table 2) at 2.15 Mgal/d.

Rapid development of the Cheswold aquifer occurred from 1952 to the late 1960's. Pumpage for 1953 averaged 3.2 Mgal/d and represents an increase of about 1.1 Mgal/d over the estimated pumpage for the late 1940's and early 1950's.

All production wells tapping the Cheswold and Piney Point aquifers prior to 1978 are listed in Table 2 (Appendix II), with average pumping rates for selected periods from pre-1952 to 1977. The selected periods shown are consistent with the time intervals used in the transient simulation and are discussed below.

Figure 6 shows average daily pumpage from the Piney Point and Cheswold aquifers during the period 1952-77. Early data for this plot are based on pumpages reported by Marine and Rasmussen (1955); the period 1957-67 reported by Sundstrom and Pickett (1968); and recent (1968-77) data inventoried during the summer of 1977. Withdrawal from the Piney Point aquifer from 1957 to 1967 was based on estimates reported by Sundstrom and Pickett (1968), and recent pumpage data were based on an inventory of users.

In general, pumpage from the Cheswold aquifer gradually increased until the early 1970's. The period 1974-77 showed a reduction in withdrawal of about 1.0 Mgal/d, reflecting the emphasis placed on the Piney Point aquifer as a source of supply.

The largest users of water from the Piney Point aquifer in Kent County are the City of Dover and Dover Air Force Base. Prior to 1957, the only withdrawal from the Piney Point aquifer in the County was from a production well in the Town of Wyoming. This well (Jd42-2), drilled in 1947, has produced an estimated 0.06 Mgal/d during the past 30 years. With the drilling of a production well (Kd11-8) at a vegetable cannery in Woodside in 1959, withdrawal increased significantly. Pumpage from the Piney Point aquifer in Delaware further increased with the drilling of the following large capacity production wells: Kd51-5 at a poultry processing plant in Felton (1960), Je32-5 at Dover Air Force Base in Dover (1963), and Dover production wells Id53-2, Id53-3, Jd14-15, Jd23-1, Jd25-3, Jd34-1, and Je12-13 drilled from 1962 to 1975. Total Piney Point aquifer pumpage in Kent County averaged about 3.4 Mgal/d in 1977 (Leahy, 1979a).

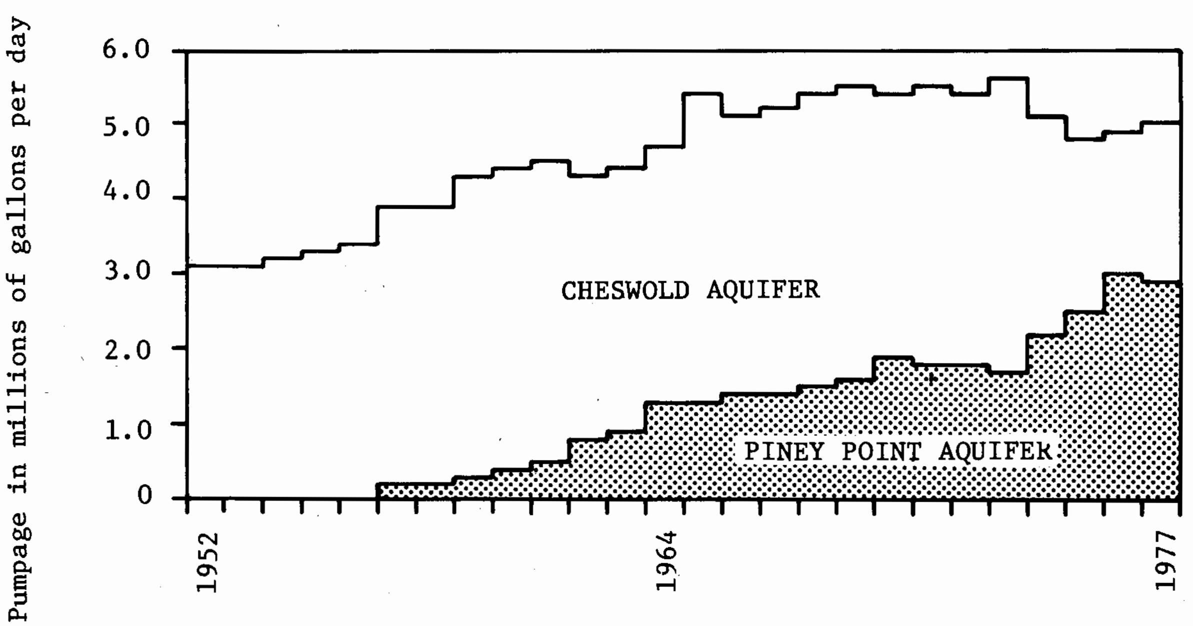


FIGURE 6. AVERAGE DAILY PUMPAGE FROM THE PINEY POINT AND CHESWOLD AQUIFERS, 1952-77.

Transmissivity, Hydraulic Conductivity, and Specific Capacity

Data are sparse for determining hydraulic properties of the Magothy aquifer in the study area. Only one well Id31-26 (Figure 4) is screened in the Magothy aquifer. The specific capacity of this well was reported to be 2.5 gallons per minute per foot [(gal/min)/ft] of drawdown after 1 day of pumping. Cushing, Kantrowitz, and Taylor (1973) estimated the coefficient of storage for the Magothy aquifer to be 0.0001. Using a technique described by Meyer (1963) and the estimated storage coefficient of 0.0001, transmissivity of the Magothy aquifer was estimated as 1,000 feet squared per day (ft^2/d). Because further information is lacking, the transmissivity of the Magothy aquifer used in the model was therefore assumed to be 1,000 ft^2/d for the entire study area.

The distribution of transmissivity (Figure 7) for the Piney Point aquifer within the study area was refined by use of a single-layer digital model (Leahy, 1979a). The transmissivities are based on aquifer-test data collected at 15 locations throughout the study area and on calibration of the single-layer model. Transmissivities of the Piney Point and Cheswold aquifers determined by aquifer tests are given in Table 3 (Appendix II). Transmissivities reported for the Piney Point aquifer range from a high of 7,350 ft^2/d for well Jd45-7 (Figure 4) near Lebanon, to a low of 26 ft^2/d for well Me15-29 (Figure 4) near Milford. Although both Piney Point and Cheswold aquifers are recharged by vertical leakage, the short duration of most of the aquifer tests precluded observing the effects of this leakage in the drawdown data. Thus, the nonleaky methods of analysis of aquifer tests were considered adequate for many of the tests.

The specific capacities of wells in the Cheswold aquifer range from 1.0 (gal/min)/ft after 4 hours of pumping, to 16.7 (gal/min)/ft after 1 day of pumping. Table 4 (Appendix II) lists the specific capacities, estimated transmissivities, and method of estimation (Brown, 1963; Meyer, 1963) of 18 wells in the study area. The transmissivity of the Cheswold aquifer appears to vary widely over the study area. Highest values are reported for the Dover and Dover Air Force Base areas and the transmissivity decreases about an order of magnitude in the surrounding area. This variability in the transmissivity of the Cheswold aquifer around Dover was also noted by Sundstrom and Pickett (1968). They reported that northwest, west, and south of the Dover-Dover Air Force Base area, the Cheswold aquifer has poor to fair water-yielding characteristics. Hydraulic conductivity, based on values of transmissivity and aquifer thickness, ranges from 100 ft/d to 4 ft/d. Lithologically, these values represent a coarse to medium sand and a fine to very fine sand, respectively (Lohman, 1972).

The transmissivity of the Cheswold aquifer also was determined by aquifer-test analysis (Table 3). The transmissivity determined from aquifer tests and specific capacity data ranges from 7,400 ft^2/d for well Jd14-17 at the treatment-plant site in Dover, to 350 ft^2/d for well Ke12-17 at the county pumping station in Magnolia. Figure 8 shows the transmissivity distribution for the Cheswold aquifer that was used in the multilayer model. The map was initially prepared using data shown in Tables 3 and 4; only minor adjustments were required for model calibration.

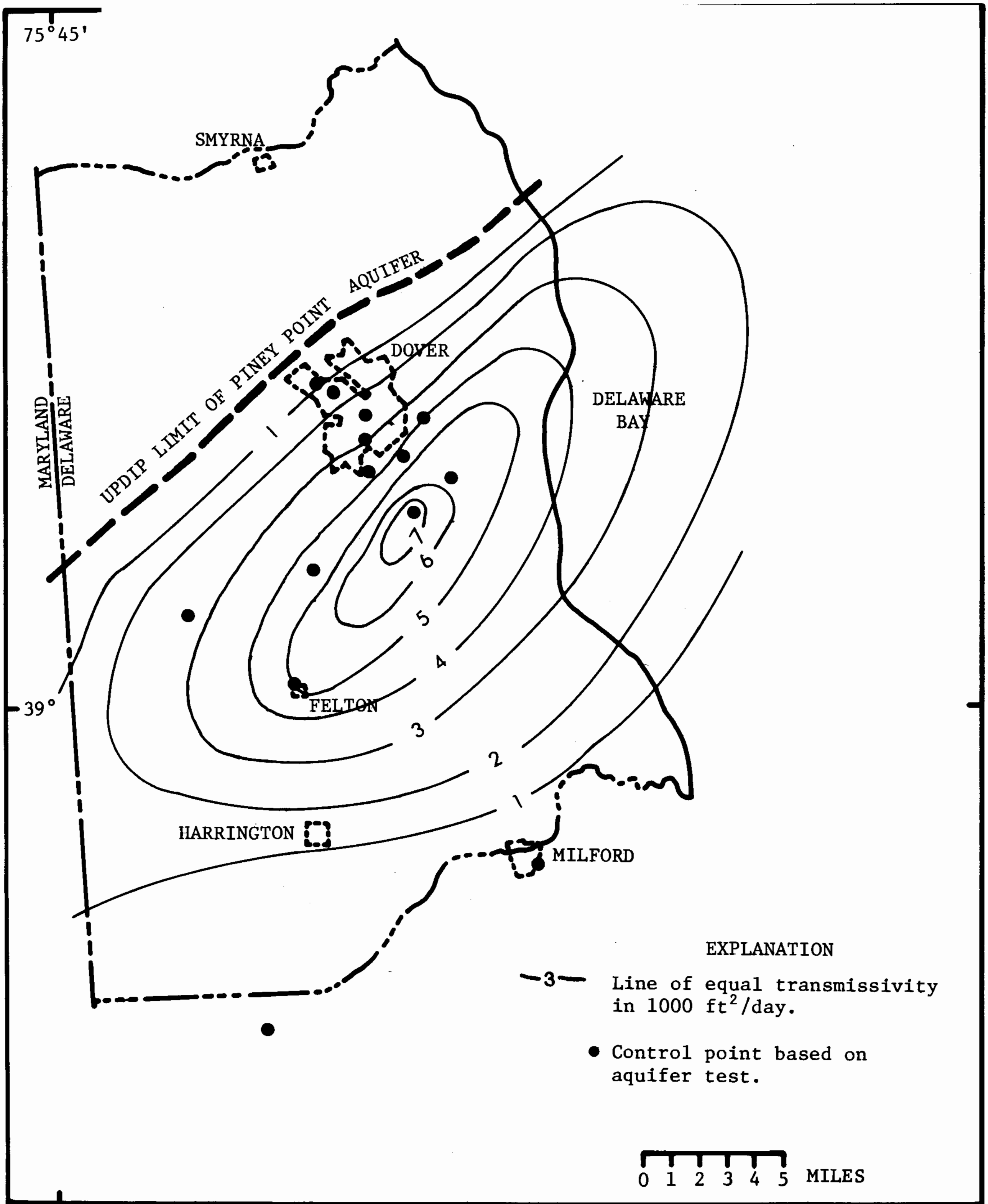


FIGURE 7. TRANSMISSIVITY OF THE PINEY POINT AQUIFER USED IN THE MODEL (FROM LEAHY, 1979A).

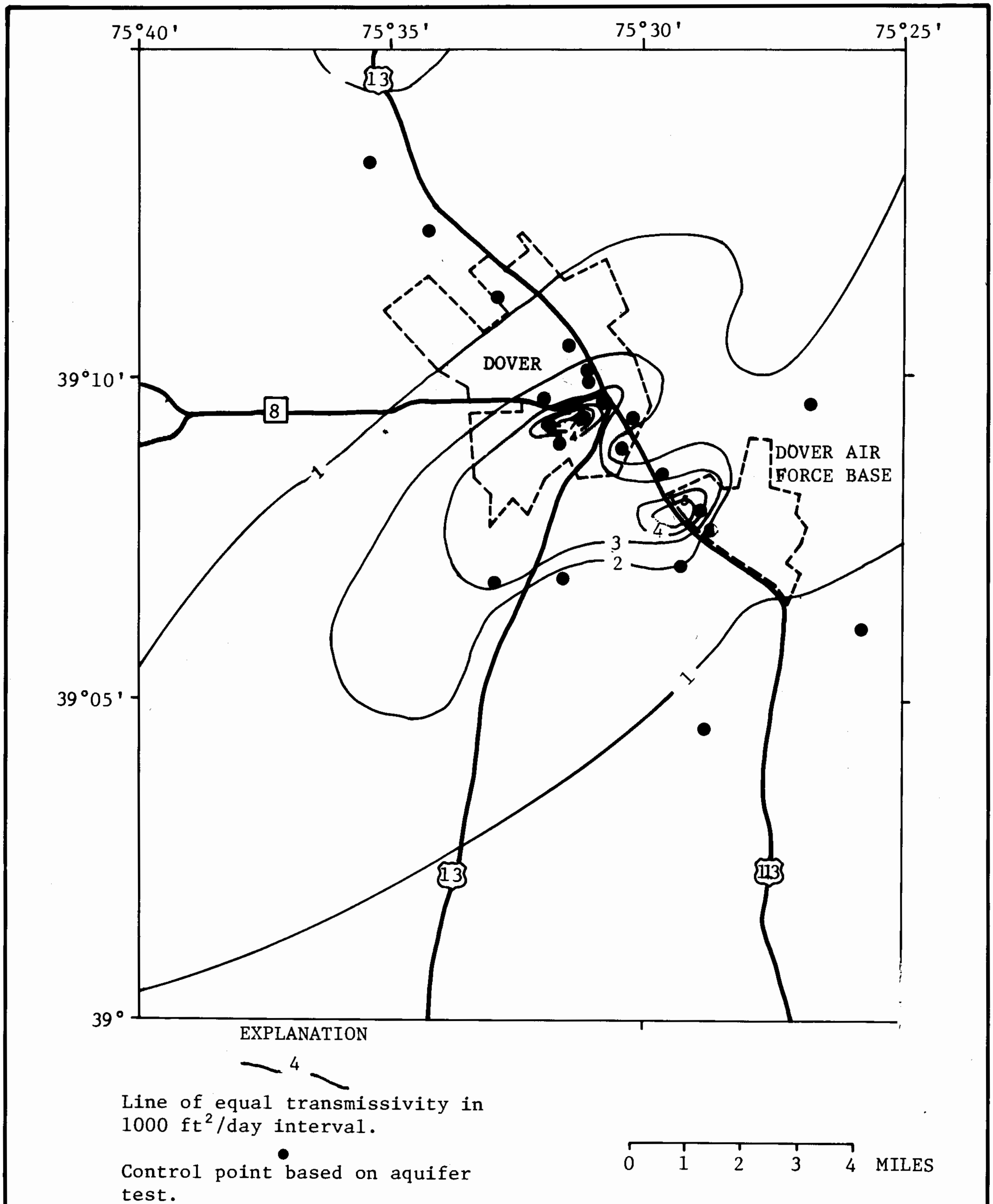


Figure 8 - TRANSMISSIVITY OF THE CHESWOLD AQUIFER USED IN THE MODEL.

The transmissivity of the unconfined aquifer was reported by Johnston (1973, 1977) and ranges from 1,000 to 11,000 ft^2/d in the study area. Hydraulic conductivity in the study area ranges from about 50 to 100 ft/d.

Storage Coefficients

The storage coefficient of the Magothy aquifer in the study area is unknown. However, Cushing, Kantrowitz, and Taylor (1973) reported that $1.0x10^{-4}$ is typical of the Magothy aquifer on the Delmarva Peninsula.

Sundstrom and Pickett (1968) reported two values of storage coefficient for the Piney Point aquifer. The coefficients are essentially the same ($3.0x10^{-4}$) and are based on aquifer tests at the Dover Air Force Base and Cambridge, Maryland. Additional aquifer tests conducted since 1968 by the U.S. Geological Survey indicate the aquifer storage coefficient ranges from a high of $3.6x10^{-4}$ at Denton, Maryland, to a low of $1.9x10^{-4}$ at Greensboro, Maryland.

Sundstrom and Pickett (1968) reported the storage coefficient of the Cheswold aquifer to be $6.2x10^{-3}$ at the East Dover Elementary School site and $3.1x10^{-4}$ at the Danner Farm site. The value determined at the school site is probably in error because the first drawdown was measured about 60 minutes after the test started. Thus, the storage coefficient could not accurately be determined. An aquifer test conducted by the U.S. Geological Survey at the Dover treatment plant in 1977 indicates a storage coefficient of $1.4x10^{-4}$ for the Cheswold aquifer; this value correlates well with the reported value of $3.1x10^{-4}$ at the Danner Farm site.

The specific yield of the unconfined aquifer has been determined at many locations on the Coastal Plain of Delaware. Johnston (1977) reported that a value of 0.15 is representative of the aquifer.

Potentiometric Surface and Head Changes

The water level in the Magothy aquifer has been measured at only one location in the study area: well Id31-26, at Cheswold. When the well was completed in 1966, the water level was approximately at sea level. Because major pumping centers of the Magothy aquifer are located a considerable distance from Kent County, no appreciable change in water level has been observed in this well during the past 11 years.

Sparse data exist on the water levels in the Piney Point aquifer before 1952. Based on water-level data reported by Sundstrom and Pickett (1968) for wells at the mouth of the Mahon River and at Dover Air Force Base, water levels probably declined as much as 6 to 14 feet in the Dover area prior to 1952. This range of values is based on a prepumping (1893) water level measured relative to an unknown tidal datum. Ground-water development of this aquifer did not begin until 1957 and heads declined initially in response to pumping in the overlying Cheswold aquifer. Observed water levels in the Piney Point aquifer have declined as much as 110 feet in the 25-year period 1952-77. The potentiometric surface of the Piney

Point aquifer for June 1977 is shown in Figure 9. Although few measurements of water levels in the Piney Point aquifer are available for 1952, a generalized potentiometric surface for 1952 was constructed. Figure 10 shows the head difference that occurred in the 25-year period 1952-77.

Three long-term observation wells screened in the Piney Point aquifer are maintained in Delaware. Two of the wells, Je32-4 at Dover Air Force Base and Id55-1 at White Oak Road, are located in or near Dover (Figure 4). Continuous water-level recorders have been in use on these wells since 1957 and late 1969, respectively. Water-level changes in these two wells (Figures 21 and 22) reflect seasonal fluctuations in pumpage by the City of Dover. The third well, Nc13-3 at Greenwood, is located 13 miles from the nearest pumping well. Water-level records for this observation well have been continuously maintained since it was drilled in the fall of 1970. The observed water levels indicate this well (Nc13-3) is unaffected by seasonal fluctuations in pumpage (Figure 25) but, rather, reflects long-term regional trends in pumpage.

Sundstrom and Pickett (1968) reported that the observed head in the first well drilled to the Cheswold aquifer in Dover in 1893 was 12 feet above sea level. A prepumping potentiometric surface for the aquifer (Figure 11) was reconstructed by removing the 1952 drawdown cone (Figure 13) from the 1952 potentiometric surface (Figure 12) and recontouring this area using the 1893 water-level measurement.

A potentiometric surface map based on June 1977 water-level measurements in the Cheswold aquifer is shown in Figure 14. The areal distribution of head decline for the 25-year period 1952-77 is shown in Figure 15.

Water levels in the Cheswold aquifer have been monitored continuously at three observation wells in the Dover area. Recorders were installed on well Id55-2 at White Oak Road from 1969 to 1972 and 1976 to 1977 (Figure 23), and on well Jd14-1 at Division Street from 1972 to 1977 (Figure 24). Because water-level responses of these wells are similar, data collected at the Division Street site were used to estimate missing data (1973-75) at the White Oak site. The third observation well, Jd25-1 (Figure 25), is located about midway between the pumping centers of Dover and Dover Air Force Base. Water levels in this well were monitored continuously from 1963 through 1970. Observations at this well were discontinued in 1970 because pumping tests showed evidence of a cracked casing and water appeared to be entering the well from the overlying unconfined aquifer. The exact time cracking occurred is unknown. However, observed water levels at this site remained relatively constant from 1967 to 1970 and suggest that the well was damaged in 1967.

Water levels in the unconfined aquifer fluctuate seasonally reflecting changes in aquifer storage due to variable rates of evapotranspiration and recharge. No measurable long-term decline in water levels has been observed in the unconfined aquifer (Johnston, 1977). However, the low base flow of streams to the north of Dover strongly suggests that some water from the unconfined aquifer is moving downward to the Cheswold aquifer rather than discharging to streams (Johnston and Leahy, 1977). Water-level adjustments in the unconfined aquifer resulting from this modification of the local flow pattern were not observed because (1) major pumpage increases in the Cheswold aquifer occurred prior to a detailed investigation of the unconfined aquifer in the area, and (2) the water-level adjustments over the leakage area were probably small relative to the seasonal fluctuation of the water table.

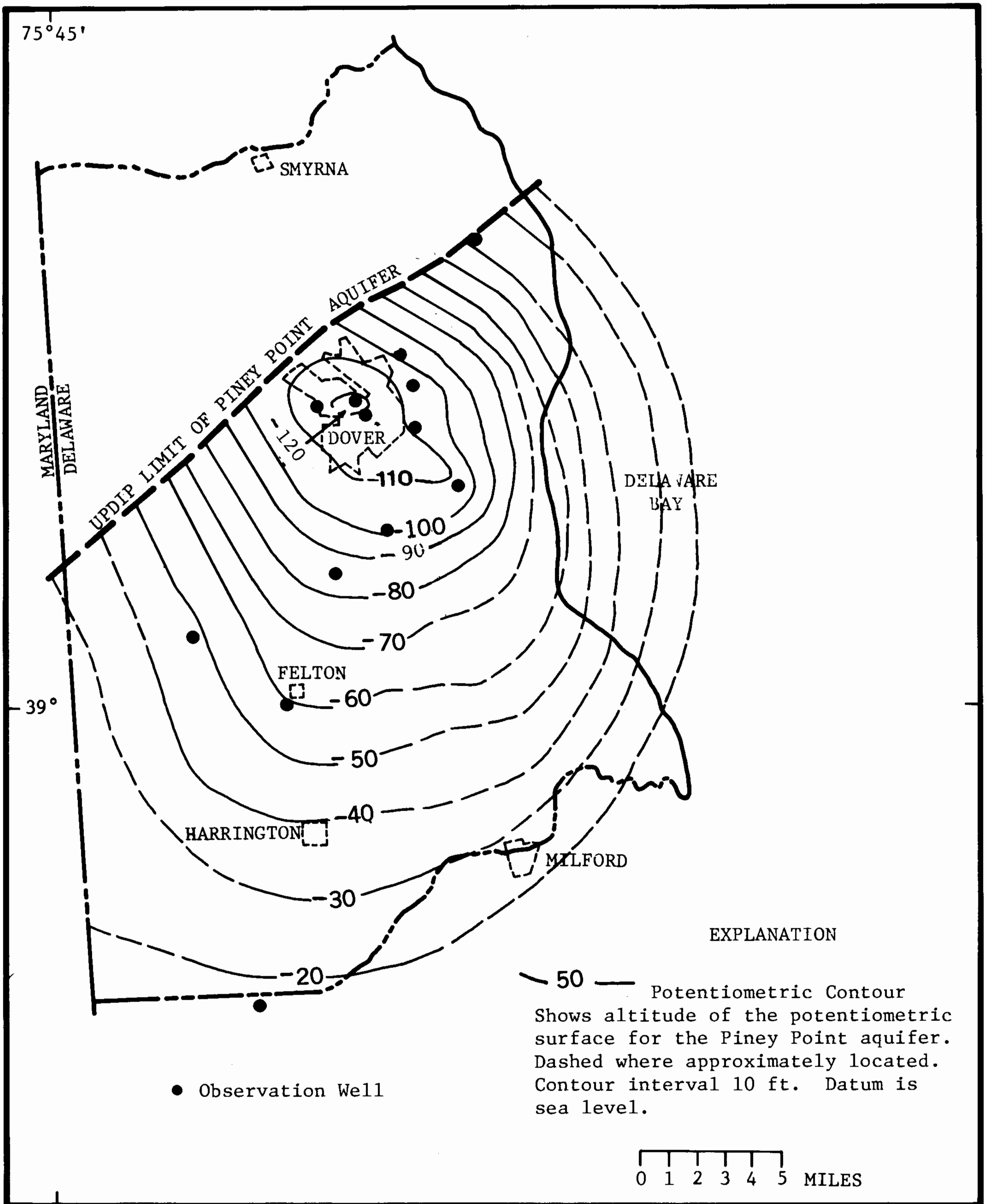


FIGURE 9 - POTENTIOMETRIC SURFACE OF THE PINEY POINT AQUIFER, JUNE 1977.

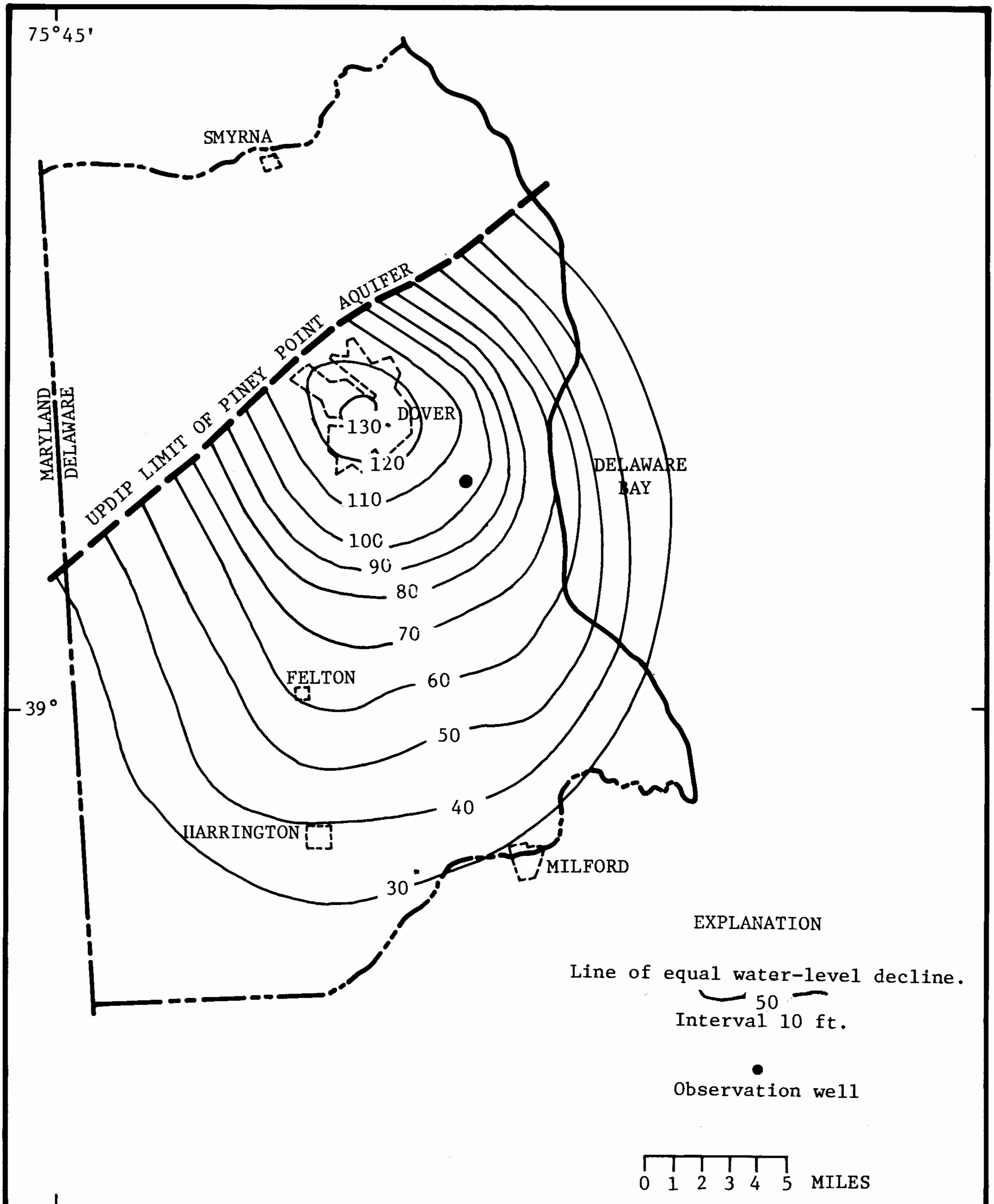


FIGURE 10 - HEAD DECLINES IN THE PINEY POINT AQUIFER, 1952-77.

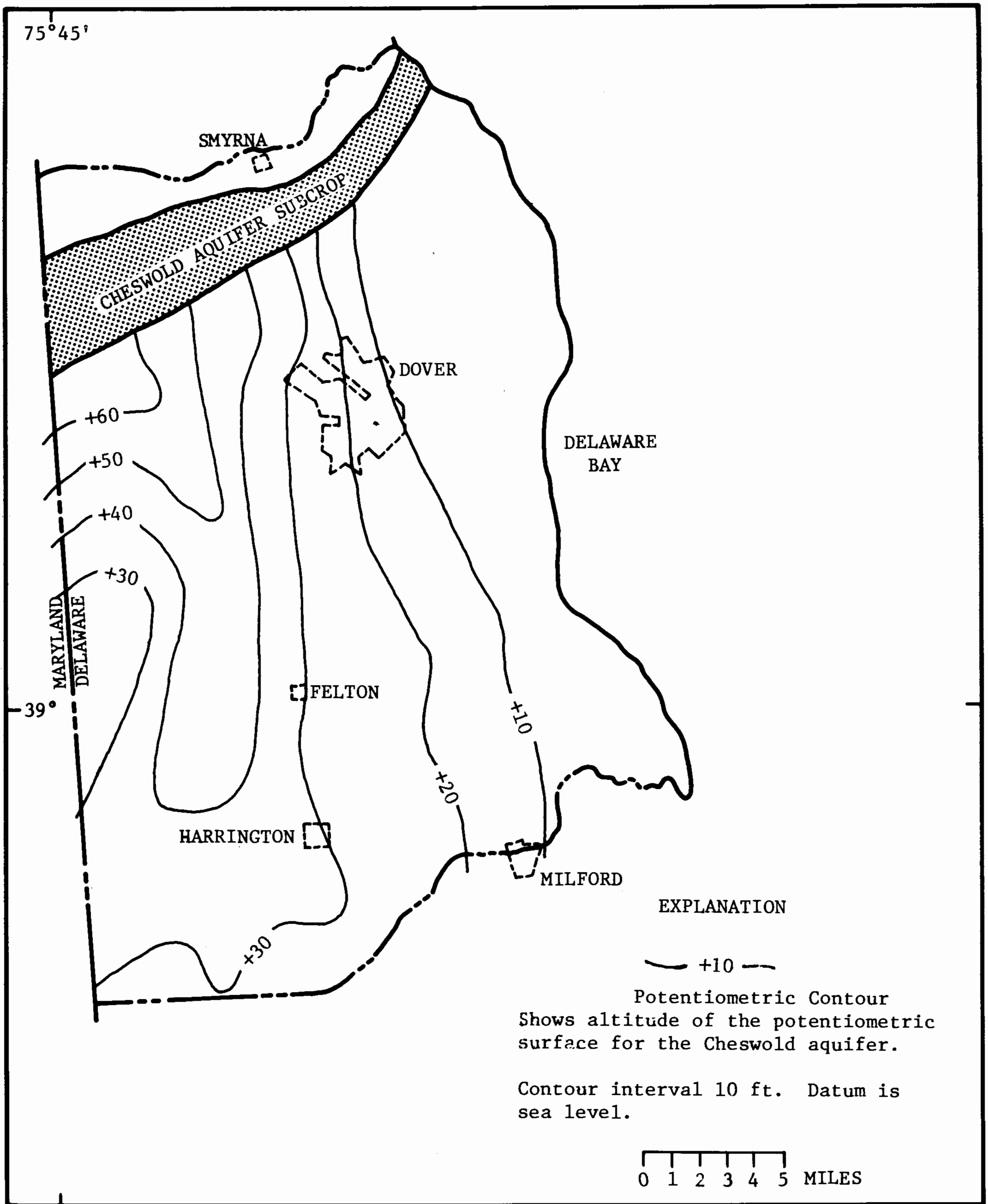


FIGURE 11 - GENERALIZED PREPUMPING POTENTIOMETRIC SURFACE OF THE CHESWOLD AQUIFER.

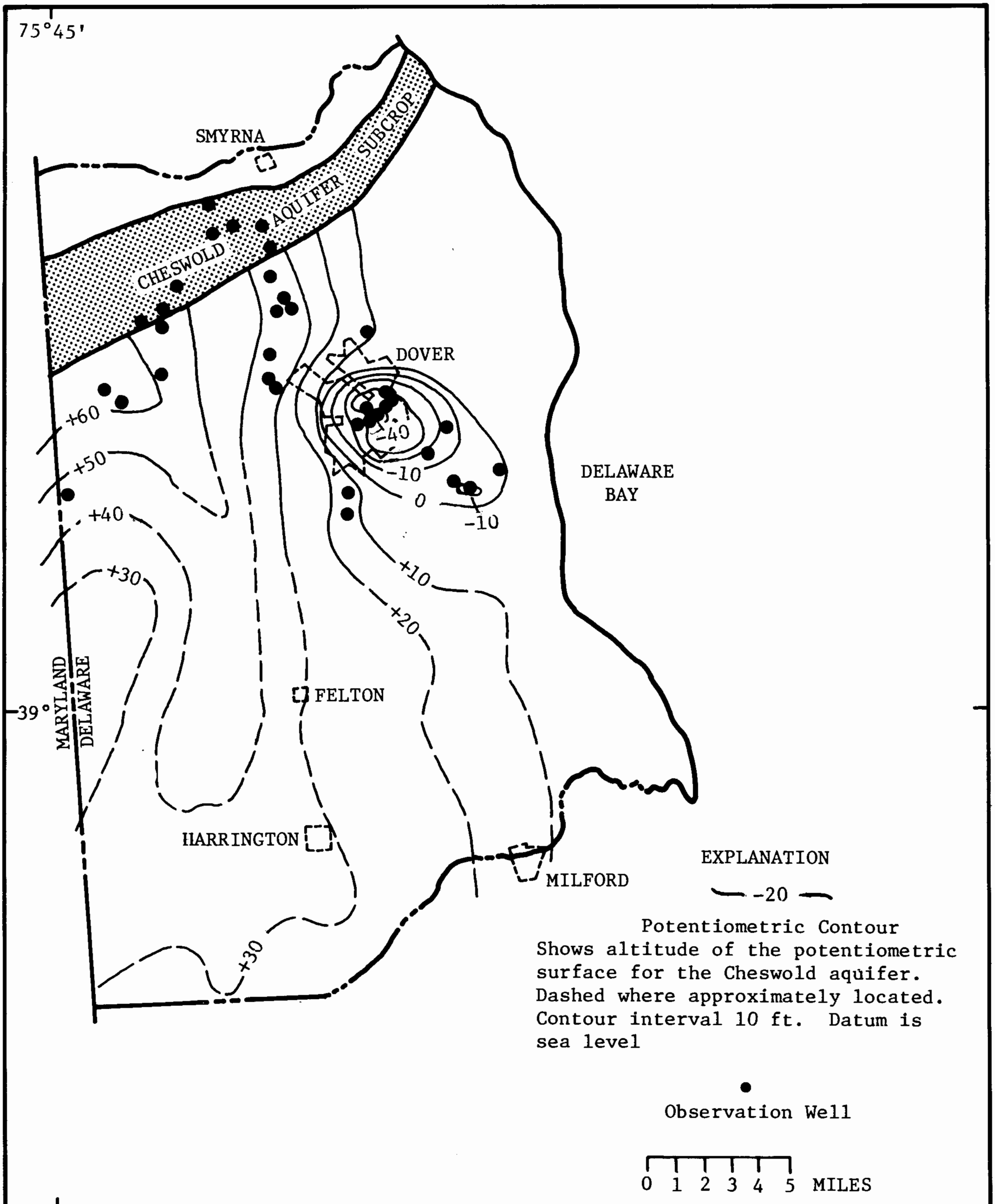


FIGURE 12 - POTENTIOMETRIC SURFACE OF THE CHESWOLD AQUIFER, 1952.

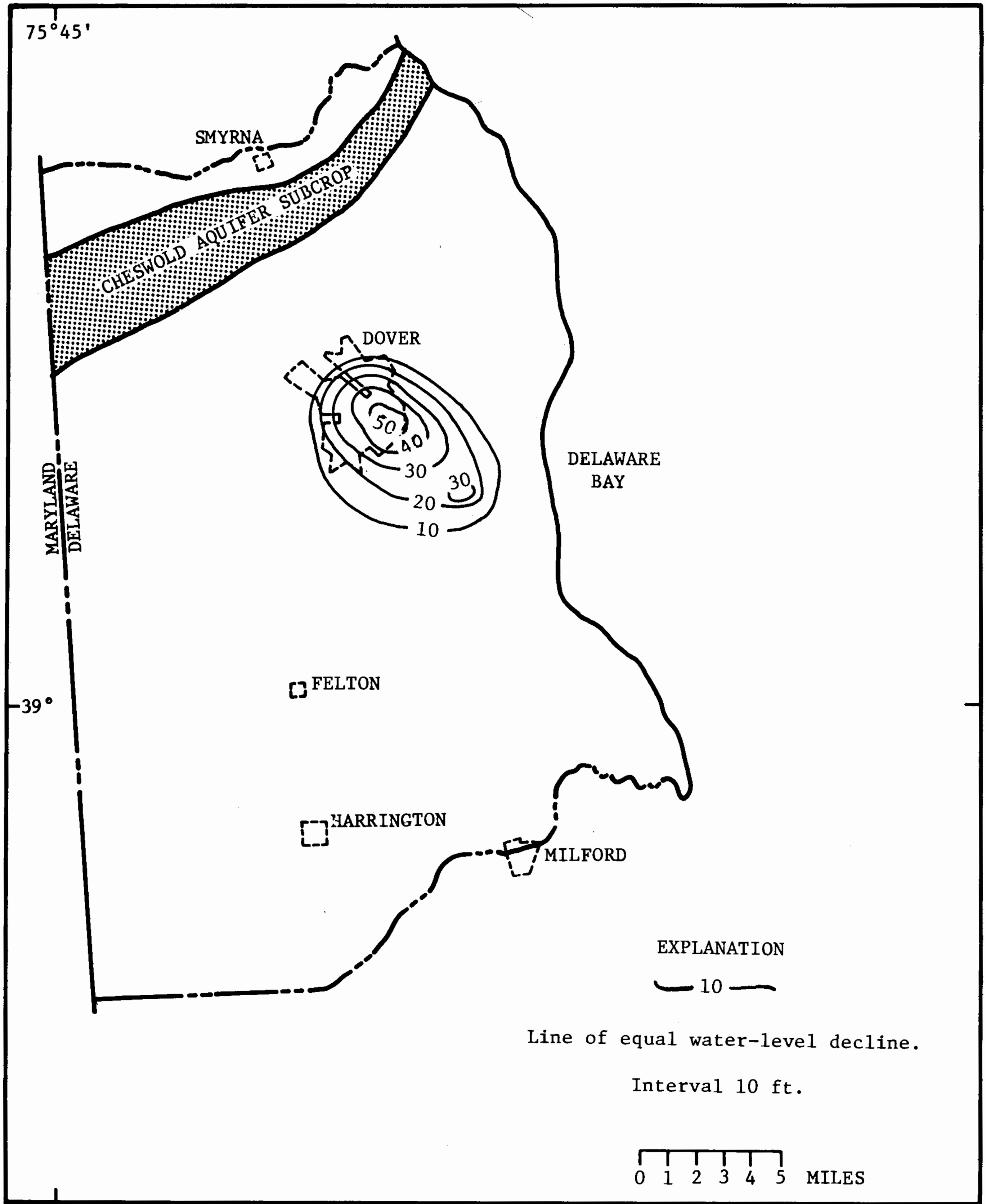


FIGURE 13 - HEAD DECLINES IN THE CHESWOLD AQUIFER, PREPUMPING TO 1952.

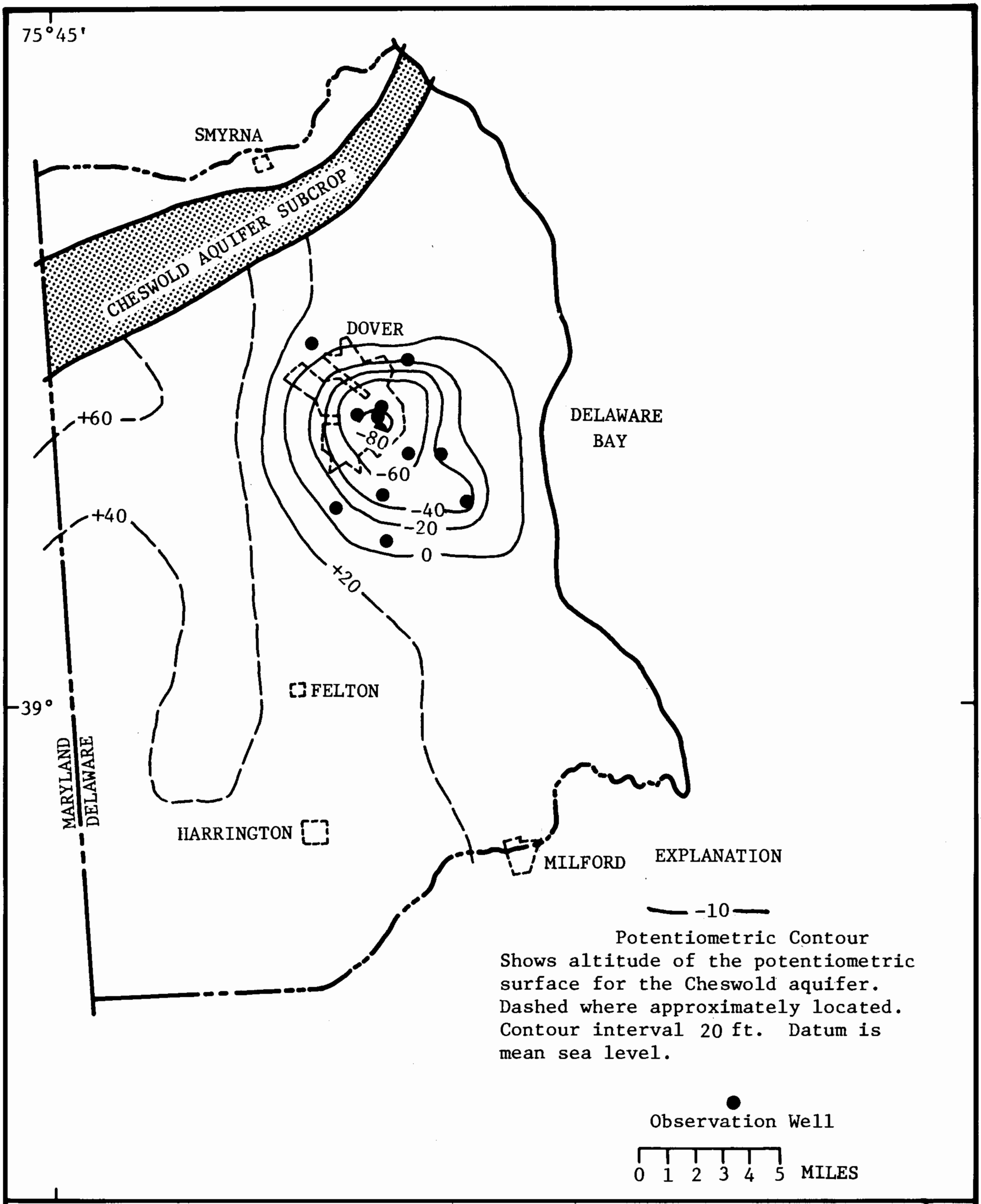


FIGURE 14 - POTENTIOMETRIC SURFACE OF THE CHESWOLD AQUIFER, JUNE 1977.

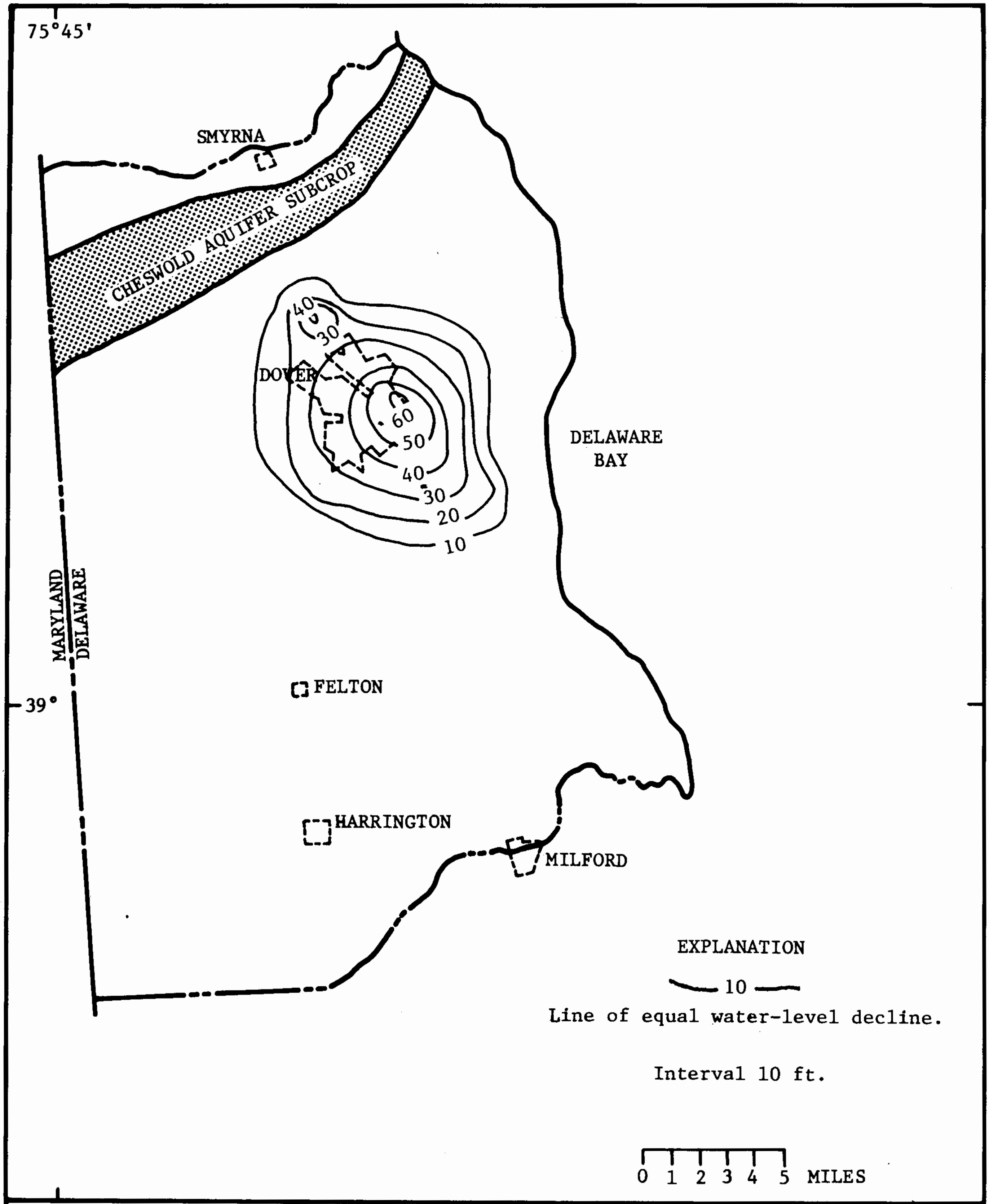


FIGURE 15 - HEAD DECLINES IN THE CHESWOLD AQUIFER, 1952-77.

Hydrogeology of Confining Beds

Lithologic Character

Three areally extensive confining beds trending across the Delmarva Peninsula and into southern New Jersey separate the major aquifers in the study area. The confining beds, ranging in age from Cretaceous through Miocene, dip southeastward and vary from approximately 100 feet to 560 feet in average thickness across Kent County.

The deepest of the three confining beds separates the Magothy and Piney Point aquifers, and includes the Nanjemoy, Pamunkey, Monmouth, and Matawan formations, and the Rancocas Group. The average thickness of the confining bed is about 560 feet in the study area and the age of the unit varies from Late Cretaceous to Early Eocene.

A Miocene age confining bed separates the Piney Point and Cheswold aquifers and averages 100 feet in thickness over the study area. Grain-size analyses of core samples from New Jersey indicated the confining-bed material ranged from silty clay to clayey silt (Nemickas and Carswell, 1976), whereas analyses of core samples taken in Delaware indicated the material ranged from clayey fine sand to silty clay (Leahy, 1976).

A number of minor aquifers in Kent County are considered herein as part of the uppermost confining bed. In particular, the Federalsburg and Frederica aquifers are included as sandy zones in the Miocene age (Chesapeake Group) confining bed that separates the Cheswold and unconfined aquifers. The confining bed is a sandy silt that averages about 100 feet in thickness over most of the study area.

All of the confining beds consist mainly of silt. However, the clay content of the sequence of confining beds increases with depth. Analysis of geophysical logs at the Greenwood test well (Nc13-3) by Talley (1975) indicated a much higher clay content in the confining bed below the Piney Point aquifer than in the confining bed above. Talley also reported that the confining bed overlying the Cheswold aquifer contains a greater percentage of very fine sand than the confining bed separating the Piney Point and Cheswold aquifers. Geophysical logs of the Dover Air Force Base well (Je32-4) indicate the same shift in grain size of the confining beds with depth (Rasmussen, Groot, and Depman, 1958). In this report, the three confining beds will be referred to as follows: (1) clayey confining bed, which separates the Piney Point and Magothy aquifers; (2) silty confining bed, which separates the Piney Point and Cheswold aquifers; and (3) sandy confining bed, which separates the Cheswold and unconfined aquifers (Table 1 and Figure 5).

Hydraulic Properties

Hydraulic properties of confining beds are difficult to obtain. In general, these values can be determined either in the laboratory or through analysis of long-duration, complex, aquifer tests. The aquifer-test approach involves measuring heads in the confining bed with pressure transducers placed at different depths. Aquifer tests of confining beds are time consuming, expensive, and are not commonly conducted. On the other hand, undisturbed cores for laboratory analysis are difficult to obtain. Because of these difficulties, few values of the hydraulic properties of confining beds have been determined in Kent County.

The vertical hydraulic conductivity and specific storage of the clayey confining bed are unknown. The abundance of clay observed on the geophysical logs, however, strongly suggests that the hydraulic conductivity of the clayey confining bed is significantly lower than the conductivity of the overlying silty confining bed, which has less clay.

Few values of the hydraulic properties of the silty confining bed have been determined. The few reported values of vertical conductivity show a marked trend along the strike of the silty confining bed. Vertical conductivity values range from a minimum in New Jersey and increase an order of magnitude southwestward across Delaware to a maximum at Preston, Maryland. Nemickas and Carswell (1976) reported values of vertical hydraulic conductivity determined from four core samples taken about 20 miles northeast of Dover, in Cumberland County, New Jersey, that range from 2.0×10^{-5} to 5.2×10^{-5} ft/d. In Delaware, a 23-day aquifer test was conducted near Dover to determine vertical conductivity and specific storage. Test results (Leahy, 1976) indicated vertical conductivity ranges from 4.0×10^{-5} to 9.0×10^{-5} ft/d, and specific storage ranges from 3.0×10^{-6} to 6.0×10^{-6} ft^{-1}. A single-layer model (Leahy, 1979a) of the Piney Point aquifer in the Dover area indicates hydraulic conductivity and specific storage of the silty confining bed probably are 3.0×10^{-5} ft/d and 6.0×10^{-6} ft^{-1}, respectively. On the Maryland side of the Delmarva Peninsula, vertical conductivities of the silty confining bed determined from cores taken near Preston, Maryland, 35 miles southwest of Dover, were 2.0×10^{-4} and 7.3×10^{-3} ft/d (Williams, 1979).

The sandy confining bed separates the Cheswold and unconfined aquifers everywhere except in the narrow subcrop of the Cheswold aquifer located north of Dover. The hydraulic properties of this confining bed are somewhat heterogeneous (Johnston and Leahy, 1977), although laboratory values of hydraulic conductivity and specific storage for this confining bed have not been determined. Lithologic descriptions imply that hydraulic conductivity of this confining layer is higher than that of the underlying, silty confining bed.

Wolff (1970) reported hydraulic diffusivity [the ratio of vertical hydraulic conductivity to specific storage (K_v/S_s)] of an upper Miocene confining bed near Salisbury, Maryland, to be 2.7 ft^2/d. The sandy confining bed which separates the Cheswold and unconfined aquifers in the Dover area appears to be similar lithologically to the confining bed in the Salisbury area. Because of this similarity, Wolff's value was used to estimate hydraulic conductivity of the sandy confining bed in the Dover area. Leahy (1976) reported hydraulic diffusivity of the silty confining bed separating the Piney Point and Cheswold aquifers as 6 to 30 ft^2/d. Assuming specific storage values of the sandy and silty confining beds are the same, a comparison of diffusivities reported by Leahy (1976) and Wolff (1970) suggests that hydraulic conductivity of the sandy confining bed is between 2 and 10 times greater than the hydraulic conductivity of the silty confining bed. Thus, hydraulic conductivity of the sandy confining bed probably ranges from 8.0×10^{-5} to 4.0×10^{-4} ft/d.

AQUIFER SIMULATION

General Methods

Over the past few years, digital modeling in ground-water hydrology has become increasingly important. The models use digital computers to solve the differential equations that describe ground-water flow by either finite-difference or finite-element techniques. As numerical techniques improved and larger computers became available, complex ground-water problems could realistically be solved. Appel and Bredehoeft (1976) have documented the status of ground-water modeling in the U. S. Geological Survey. The model used during this study was the finite-difference flow model developed by the U. S. Geological Survey (Trescott, Pinder, and Larson, 1976; Trescott, 1975).

Initially, large multilayer aquifer systems were modeled in a piece-wise fashion. Flow in an individual aquifer in the system was simulated using a two-dimensional model. The model assumes that (1) all flow within the modeled aquifer occurs in a horizontal plane, and (2) heads in adjacent unmodeled aquifers are not affected by heads in the modeled aquifer.

Vertical flow or leakage from adjacent aquifers into the modeled aquifer through adjacent confining beds is computed analytically. The analytical solution of vertical leakage is obtained on the assumption that heads in the adjacent unmodeled aquifer are known and remain constant with time. Leakage is adjusted in successive increments of time in response to head changes in the modeled aquifer. However, head changes in adjacent aquifers are not considered in the analytical solution. In reality, heads in adjacent aquifers are also affected by head changes in the modeled aquifer; therefore, assumptions inherent in development of the analytical solution of vertical leakage are unrealistic and will affect the model results.

To realistically model multilayer aquifer systems, three-dimensional flow models have been developed. Head changes in aquifers adjacent to the modeled aquifer are determined as an outcome of the solution process in the three-dimensional model. In a three-dimensional model, confining beds as well as aquifers are considered as discrete layers, and flow in each layer is considered to be in three dimensions. Head distributions in both the confining beds and aquifers are computed simultaneously. The number of equations needed to be solved for a three-dimensional model of a multilayer aquifer system increases dramatically compared to those needed for a two-dimensional model.

An alternative approach, which is a variation of the three-dimensional and two-dimensional approaches, was developed achieving the desired accuracy without unduly increasing the need for more computer capacity and time. These models are commonly termed "quasi three-dimensional models." The assumption of this model is that all flow in the confining beds is vertical; flow in the horizontal direction can be neglected because of the low conductivity of the confining bed.

The quasi three-dimensional approach is essentially an extension of the two-dimensional approach. The major difference between the quasi three-dimensional and two-dimensional approaches is that in the two-dimensional approach, head changes are computed for each aquifer individually, whereas, in the quasi three-dimensional approach, head changes in the entire system of aquifers are computed simultaneously. The two-dimensional approach yields a separate set of results for each aquifer in the system. These results will be incompatible with each other. However, the three-dimensional and quasi three-dimensional approaches yield one set of results for the system--the results for each aquifer being compatible with all the others in the system.

Early quasi three-dimensional models coupled the aquifers with an analytical solution representing steady-state leakage only. Storage in the confining beds was assumed to be zero. In reality, storage of confining beds is generally larger than that of aquifers because the porosity of confining beds is usually larger than that of the aquifers. Thus, the volume of water per unit head decline released from confining-bed storage may exceed that released from aquifer storage. A transient-state solution as well as a steady-state solution is needed to represent the leakage closely. An analytical solution was developed which included the effects of both steady-state and transient-state leakage (Posson, Hearne, Tracy, and Frenzel, 1980). Leahy (1979b) has demonstrated that an appreciable reduction in computer costs without accompanying loss in model accuracy can be obtained by using the more realistic analytical solution of vertical leakage in a quasi three-dimensional model.

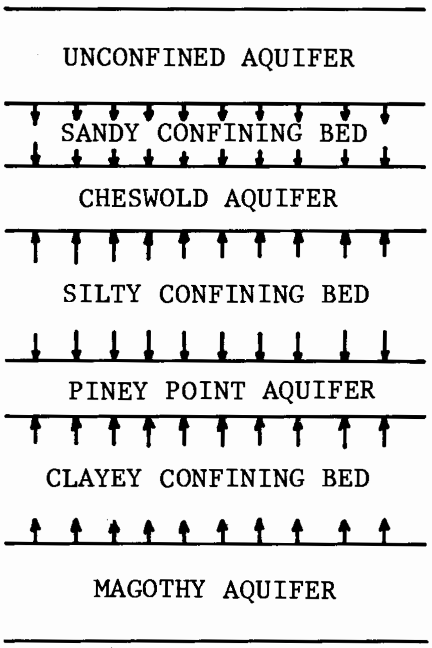
In this modeling study, the effects of transient leakage and the interactive nature of the Cheswold and Piney Point aquifers appear to be significant. Therefore, in order to accurately and efficiently model the aquifer system, a quasi three-dimensional model that included the effects of transient leakage was used. The model program and the calibration data are available in the computer files of the Delaware Geological Survey.

Conceptual Model, Boundary Conditions, and Data Requirements

Figure 16A shows a conceptual model of the aquifer flow system underlying Kent County. Under pumping conditions, ground-water flow in the system consisted primarily of downward leakage from the unconfined aquifer and lateral flow through the Cheswold and Piney Point aquifers to discharging wells. Both upward and downward leakage occurred in the confining bed separating the Piney Point and Cheswold aquifers, and little if any upward leakage occurred through the clayey confining bed. Figure 16B shows the simulated model of the conceptualized flow system. The modeled aquifers are the Cheswold and Piney Point. The Magothy and unconfined aquifers are included in the model to insure appropriate boundary conditions in the vertical direction. The following assumptions were made:

(1) Hydraulic properties of the aquifers are isotropic, and all flow within the aquifers is lateral. Flow in the confining beds is considered to be in the vertical direction only.

(2) The unconfined aquifer and subcrop of the Cheswold aquifer are treated as constant-head boundaries. The constant-head assumption for the unconfined aquifer is supported by the relative constancy of water levels in this aquifer (Johnston, 1977). The subcrop of the Cheswold aquifer is in direct contact with the unconfined aquifer and can be considered a part of that aquifer. Thus, the subcrop of the Cheswold also is considered as a constant-head boundary.



-Steady-state conditions indicated by little change in water level (Johnston, 1977)

-Appreciable downward leakage

-Ground-water movement to pumping centers

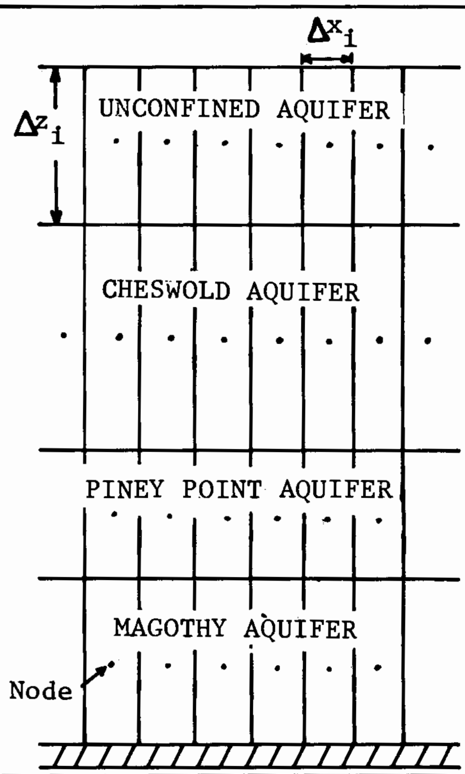
-Appreciable leakage in both vertical directions dependent on heads in adjacent aquifers

-Ground-water movement to pumping centers

-Probably very little upward flow because the confining bed is very thick and has an extremely low vertical conductivity

-Negligible head declines caused by pumpage in overlying aquifers

A. Conceptual model of flow system



-Constant head (heads may vary areally, but are constant with time); lateral flow in aquifer

-Vertical leakage between aquifers (Controlled by head gradients in aquifers and by vertical conductivity, specific storage, and thickness of confining bed.)

-Lateral flow in aquifer

-Vertical leakage between aquifers

-Lateral flow in aquifer

-Vertical leakage between aquifers

-Lateral flow in aquifer

-Impermeable boundary

B. Simulated model of flow system (Quasi-three dimensional approach).

FIGURE 16 - CONCEPTUAL AND SIMULATED MODELS OF THE MULTILAYER AQUIFER SYSTEM.

(3) Vertical hydraulic properties used for individual confining beds are assumed to be constant with depth.

(4) Water released from confining-bed storage is simulated according to the method described by Posson, Hearne, Tracy, and Frenzel (1980).

(5) The base of the Magothy aquifer is considered an impermeable boundary (no-flow boundary).

(6) Ground water is discharged only by pumping and leakage.

The modeled aquifers were discretized using a 2,784-node, finite-difference grid. The grid arrangement used for each aquifer is shown in Figure 2. The model boundaries were:

(1) Constant-head boundaries: Heads in the unconfined aquifer and in the subcrop of the Cheswold aquifer were held constant.

(2) Impermeable boundaries (zero transmissivity): All aquifers were bounded laterally with impermeable boundaries or no-flow boundaries. Wherever possible, these boundaries coincided with physical boundaries of the aquifers, such as the Piney Point aquifer pinchout to the north, south, and east. However, at some locations, such as the western edge of the model, the actual physical boundaries of the aquifers did not coincide with the modeled impermeable boundaries. These modeled boundaries, however, were located far enough from the area of interest to minimize effect on model results.

The aquifer system was simulated in both steady-state and transient-state conditions. Different geohydrologic information was required to model each type of simulation. The digital model used geohydrologic data that were defined at each model node and were considered representative for the whole grid block. Data needed and used in model simulations include:

(1) Dimensions (ΔX and ΔY) of the rectangular grid. Each aquifer was broken into blocks by a 29x24 (Figure 2) grid with variable node spacing. The highest node density was placed in the area of interest.

(2) Initial head distribution in the aquifers. The heads in all simulations were assumed to initially be in equilibrium. Initial heads in all the aquifers were set equal and the model computed the head changes resulting from pumping changes in the aquifers.

(3) The transmissivity of each aquifer.

(4) Storage coefficient of each aquifer. These data were used only in the transient-state simulations.

(5) Average thickness of each confining bed.

(6) Vertical hydraulic conductivity of each confining bed.

(7) Specific storage of each confining bed. These values were required in the transient-state simulations.

(8) Location and changes in pumping rate of wells tapping the Piney Point and Cheswold aquifers in the modeled area.

Model Calibration

Before a model can be used, it must be calibrated. The calibration of a model is accomplished through a trial-and-error adjustment of aquifer and confining-bed hydraulic parameters, within a reasonable range, to modify the model results until they closely correlate with observed data. In this study, the model was calibrated by simulating the known history of pumping from wells and comparing the computed and observed head declines (drawdowns).

Calibration involved two types of simulations. The first type simulated steady-state conditions that were assumed to exist in the aquifer system prior to 1952. This calibration allowed the refinement of the distribution of (1) the transmissivity of the aquifers, and (2) the vertical hydraulic conductivity of the confining beds. Calibration was accomplished by comparison of computed and observed water-level decline maps. The observed water-level decline maps were constructed from sparse data with most of the data being for the Cheswold aquifer. The hydraulic properties of the Piney Point, unconfined aquifers, and the confining bed overlying the Piney Point aquifer have been used and tested in several model studies (Johnston, 1977; Leahy, 1979a). Therefore, steady-state calibration in this study was designed to refine estimates of (1) transmissivity distribution of the Cheswold aquifer, and (2) the vertical hydraulic conductivity of the confining bed overlying this aquifer. Because of uncertainties concerning the assumed steady-state condition prior to 1952 and sparse water-level data on which the steady-state calibration is based, the purpose of the steady-state simulation was not to produce a highly accurate calibration but, rather, to approximate the transmissivities and hydraulic conductivities.

Steady-state simulations are considerably less expensive than transient-state simulations. Therefore, simulation of the steady-state condition was used to inexpensively refine estimates of the transmissivities of the aquifers and vertical hydraulic conductivities of the confining beds. Using these estimates as a starting point in the transient-state simulations, the number of transient-state simulations required to achieve model calibration was reduced, thus reducing the overall cost. The refined transmissivities and hydraulic conductivities were then used again as input to the steady-state simulation to assure compatibility between both transient-state and steady-state simulations.

The second type of simulation consisted of modeling the transient-state response of the aquifer system for the 25-year period 1952-77. The 25-year period was chosen because sufficient pumpage and water-level data were available for this period. Also, any residual drawdowns caused by the system not being in the assumed steady-state condition prior to 1952 would have a negligible effect on water-level declines late (1970-77) in the transient-state simulation where water-level decline data are most plentiful. The transient-state calibration refined estimates of storage coefficients of aquifers and specific storage of confining beds as well as further refining estimates of hydraulic conductivity and transmissivities used in the steady-state calibration.

Steady-State Simulation

The Kent County aquifer system was assumed to have reached a steady-state condition with a pumpage of 2.2 Mgal/d sometime prior to 1952. The assumed steady-state condition is supported by constant withdrawals from the Cheswold and Piney Point aquifers during the period from the late 1940's through early 1950's. The other aquifers in Kent County were either unpumped or slightly pumped prior to the early 1950's.

Steady-state simulations were used to determine the head decline that would be caused by a constant withdrawal of 2.15 Mgal/d from the Cheswold aquifer and 0.06 Mgal/d from the Piney Point aquifer prior to 1952. The calibration procedure consisted of adjustment of the hydraulic parameters until agreement between observed and computed drawdowns was achieved.

The unconfined aquifer in the study area has been modeled by Johnston (1977), and the Magothy aquifer is beyond the interest of this study; therefore, the unconfined and Magothy aquifers were not modeled in detail. The unconfined aquifer was considered as a constant-head boundary. The Magothy aquifer was included in the model to avoid treating the base of the Piney Point aquifer as an impermeable boundary.

The input hydraulic parameters were pumpage, initial heads, transmissivities of the aquifers and vertical conductivities of the confining beds. Before pumping started in 1893, the aquifer system was in steady state. Thus, the initial heads in each aquifer were set equal by using the concept of superposition. In a steady-state simulation of this type, only head changes resulting from pumping are of interest, and actual values of the computed heads can be ignored. Figure 17 shows the steady-state simulated and observed head changes for the Cheswold aquifer in the Dover area resulting from a total pumpage of 2.2 Mgal/d. The lack of an exact fit between the simulated and observed head declines (Figure 17) was expected. In view of the limitations of the observed data, the simulated Cheswold aquifer cone of depression compares reasonably well with the observed head-decline map.

Head declines for the Piney Point aquifer in the Dover area prior to 1952 were computed by the steady-state simulation to be between 4 and 9 feet. As previously stated, the heads were believed to have declined between 6 and 14 feet in the Piney Point aquifer prior to 1952 (Sundstrom and Pickett, 1968). Because the unconfined aquifer was treated as a constant-head boundary, no head decline was expected. Simulated drawdowns in the Magothy aquifer were insignificant.

In the steady-state calibration, the transmissivity distribution (Figure 7) used for the Piney Point aquifer was based on data used in a two-dimensional model study by Leahy (1979a). Transmissivities of the Cheswold aquifer were based on aquifer tests and specific-capacity data and refined during the course of calibration. Transmissivity used for the unconfined aquifer was based on data used in a two-dimensional model study by Johnston (1977). A constant transmissivity of 1,000 ft^2/d was used for the Magothy aquifer.

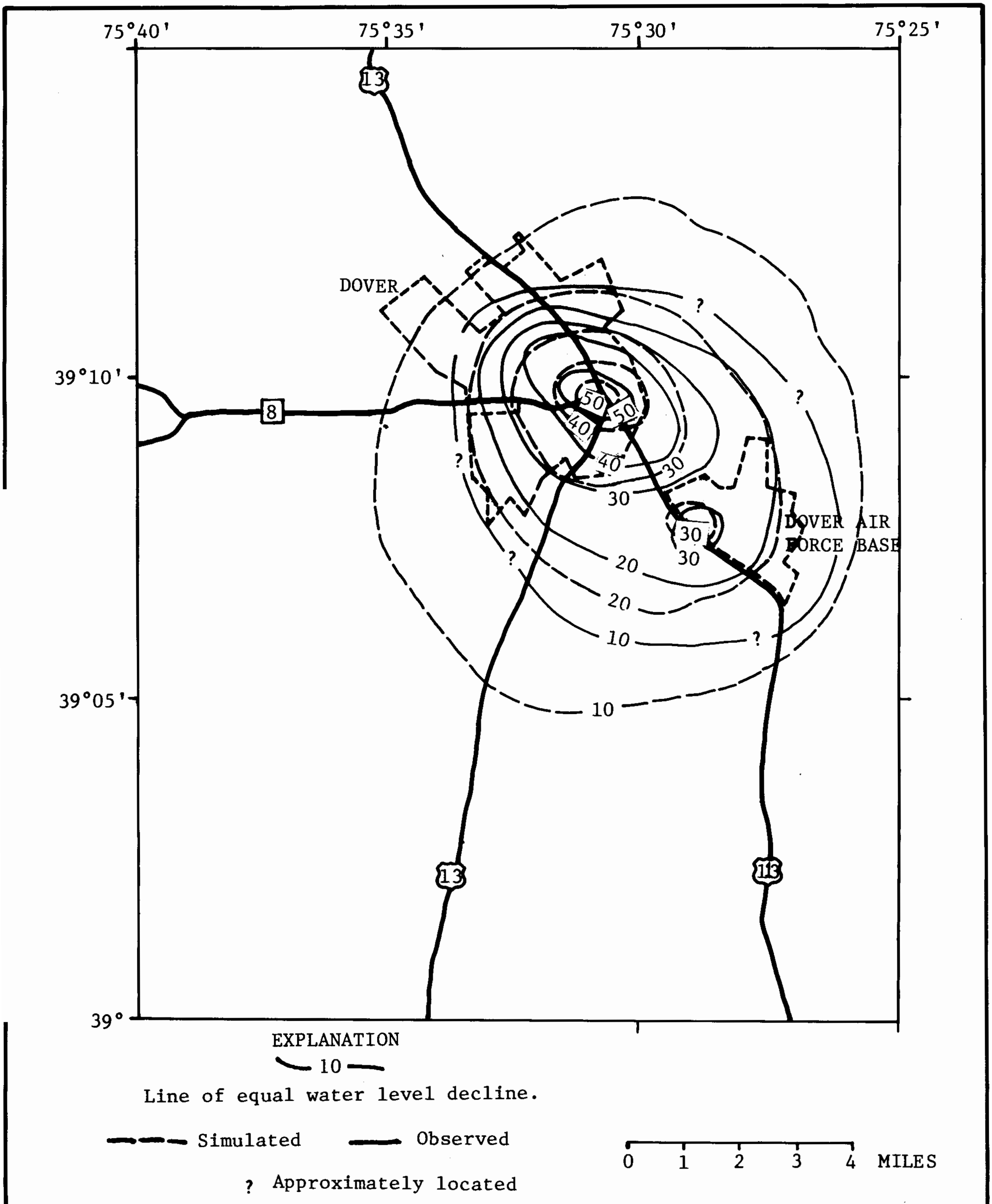


FIGURE 17 - SIMULATED AND OBSERVED HEAD DECLINES FOR THE CHESWOLD AQUIFER RESULTING FROM A TOTAL STEADY-STATE PUMPAGE OF 2.2 Mgal/d.

In the calibration process, most adjustments were made to the vertical conductivities of the confining beds because there is less confidence and control in the vertical conductivity data than in the transmissivity data. Average thickness as well as vertical conductivity of each confining bed were used in the calculation of steady-state leakage. Thickness values used were 560 feet for the clayey confining bed and 100 feet for both the silty and sandy confining beds. Adjustment of vertical conductivity compensated for errors resulting from use of an average thickness.

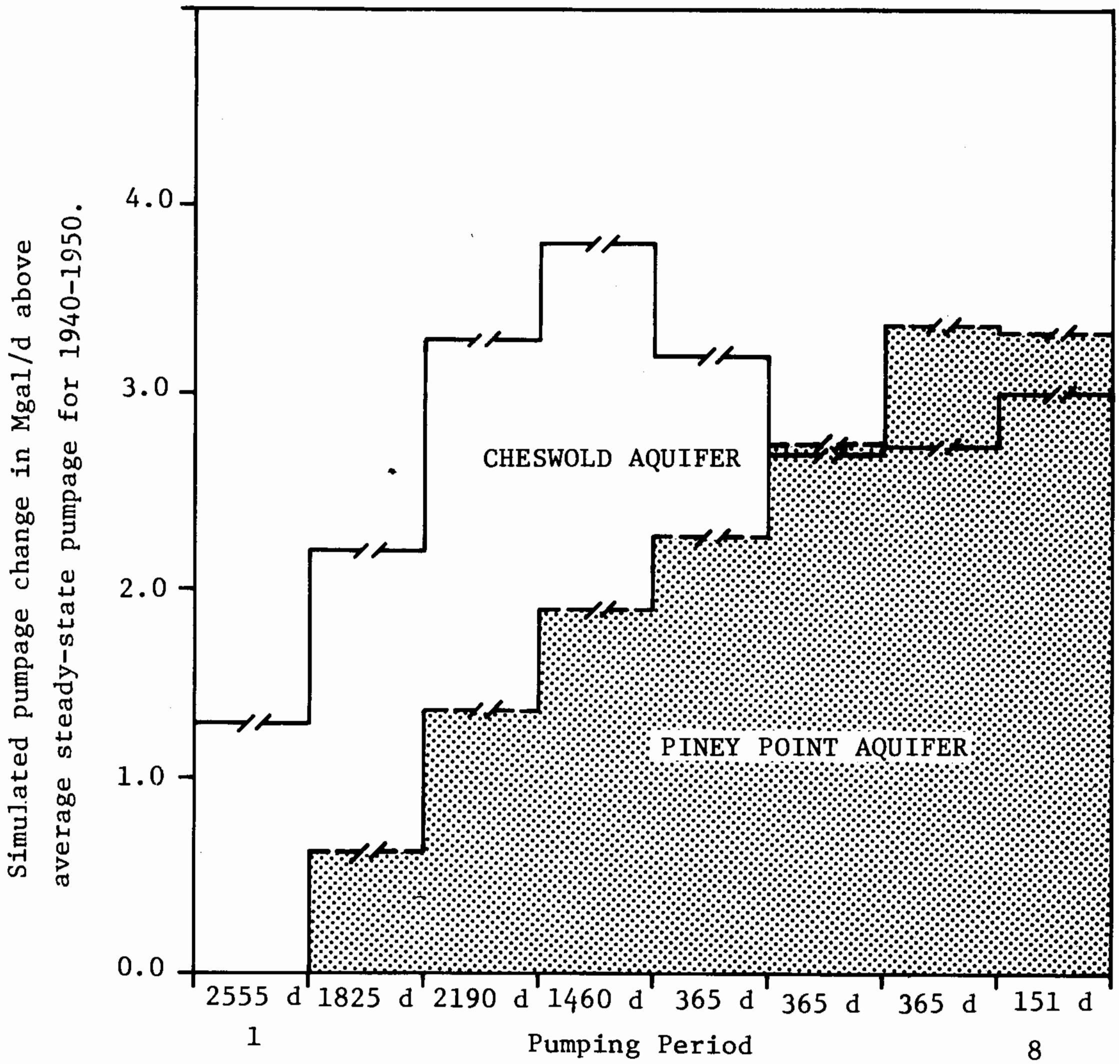
A vertical hydraulic conductivity of 5.0×10^{-10} ft/d was used for the clayey confining bed that separates the Magothy and Piney Point aquifers. A sensitivity analysis of this parameter showed that a vertical hydraulic conductivity of as much as 5.0×10^{-6} ft/d had little or no effect on model results in any aquifer in the model. Therefore, the actual value of this conductivity is not crucial to the results of the modeling study.

The vertical hydraulic conductivity of the silty confining bed that separates the Piney Point and Cheswold aquifers was initially assigned a value of 3.0×10^{-5} ft/d. This value was used in a model study of the Piney Point aquifer by Leahy (1979a). After steady-state and transient-state calibrations, the vertical hydraulic conductivity of the confining bed was found to be 2.0×10^{-5} ft/d. The small difference between the conductivity values is probably due to using the average confining-bed thickness rather than the actual thicknesses.

It was necessary, however, to determine the distribution of vertical hydraulic conductivities for the sandy confining bed that separates the Cheswold and unconfined aquifers in the Dover area in order to calibrate the model. Calibration of the model showed a range in the conductivity from 4.0×10^{-4} ft/d over most of the study area to 1.2×10^{-3} ft/d in a 32-mi^2 area northwest of Dover. Field data are unavailable for checking the model-determined conductivity in the area northwest of Dover. The conductivity used in the model is an effective value representing the ratio of vertical hydraulic conductivity to actual thickness. The higher effective conductivity determined for the area northwest of Dover is probably caused by a reduction in actual thickness or an increase in the vertical conductivity of the confining bed. Previous modeling efforts by Johnston and Leahy (1977) implied that significant leakage to the Cheswold aquifer is concentrated in the same 32-mi^2 area of the St. Jones River Basin northwest of Dover (Figure 2). Calibration of this model agreed with the conclusions of the earlier model study.

Transient-State Simulation

The transient-state simulation was designed to evaluate the response of the aquifer system to 25.5 years of pumping (January 1952 to June 1977). The simulation was divided into eight pumping periods, and the model was stressed with pumping at an average rate over each pumping period. The pumping periods vary in duration from an initial period of 2,555 days to a final period of 151 days. The changes in pumpage from the steady-state condition of the early 1950's used in the simulation are shown in Figure 18.



PUMPING PERIODS:

1-Jan. 1, 1952 - Dec. 31, 1958
2-Jan. 1, 1959 - Dec. 31, 1963
3-Jan. 1, 1964 - Dec. 31, 1969
4-Jan. 1, 1970 - Dec. 31, 1973
5-Jan. 1, 1974 - Dec. 31, 1974
6-Jan. 1, 1975 - Dec. 31, 1975
7-Jan. 1, 1976 - Dec. 31, 1976
8-Jan. 1, 1977 - June 1, 1977

d=days

FIGURE 18 - PUMPAGE CHANGE SIMULATED IN TRANSIENT STATE CALIBRATION.

Transient-state calibration involved adjustment of storage coefficients and specific storage values, and minor adjustments of transmissivities and hydraulic conductivities. These adjustments were made until (1) maps of simulated drawdown for 1952-77 compared favorably with the observed drawdown of the Piney Point and Cheswold aquifers, and (2) simulated well hydrographs compared favorably with observed well hydrographs. The calibration consisted of matching the observed head changes to within the seasonal fluctuations of the water levels in each aquifer in the system. The measured fluctuations may be 5 to 10 feet, annually. Observed and simulated head declines, 1952-77, for the Piney Point and Cheswold aquifers in the study area are shown in Figures 19 and 20, respectively. Simulated and observed hydrographs at 17 well sites are shown in Figures 21 through 30. In general, the simulated head change accurately reflected the trend of the observed water levels. Note that while water levels were rising in the Cheswold aquifer, they were dramatically declining in the Piney Point aquifer, reflecting pumpage trends in each of the aquifers.

An exact fit of the seasonal water-level fluctuations (Figures 21-30) was not possible because simulated head changes were based on pumping rates generally averaged over periods of 1 year or longer. Poor agreement between simulated and observed hydrographs occurred at two Piney Point aquifer wells. The first well, He52-2 (Figure 27), at the Bombay Hook Wildlife Refuge about 7 miles northeast of Dover, is located near the updip edge of the Piney Point aquifer (Figure 4) where the hydraulic gradient is very steep. This well is positioned in the model grid near the boundary of two nodes, and it was not possible for the model to compute an accurate hydrograph for this well. However, model results show that the observed water-level decline at this site is enveloped by the simulated water-level declines at the adjacent model nodes. Obviously, to model the area around observation well He52-2 (Figure 4) accurately would require a finer grid spacing near the well. However, because the primary area of interest is located in the Dover area, comparison of the hydrographs at this site was considered acceptable.

The second observation well where poor agreement occurred was Je12-13 (Figure 28) located on Horsepond Road in Dover. The water level in this well was measured only twice from 1975 to 1977. The measurements may not reflect the true static water level because the effects of recent pumping at this well probably caused the measured water level to be lower than the true static water level. Thus, a comparison of the simulated and observed water-level declines at this site was considered adequate.

The transmissivities of the Piney Point aquifer were not modified during the transient-state simulations because these transmissivities have been used in previous model simulations of the aquifer (Leahy, 1979a). However, the transmissivity distribution for the Cheswold aquifer was further refined during the transient-state calibration. The final transmissivity map for the Cheswold aquifer used in the model is shown in Figure 8. The transmissivity distribution shows a range from 7,400 ft^2/d to less than 1,000 ft^2/d in the Dover area.

Storage coefficients used in the model for the Piney Point and Cheswold aquifers were uniform being 3.0×10^{-4} and 1.4×10^{-4}, respectively. A uniform value of $1.0 \times 10^{-6} ft^{-1}$ for specific storage for all the confining beds was used to calibrate the model. This value is slightly lower than the values, 3.0×10^{-6} to $6.0 \times 10^{-6} ft^{-1}$, obtained in a previous aquifer test as discussed on page 29. The reason for this relatively minor difference is uncertain.

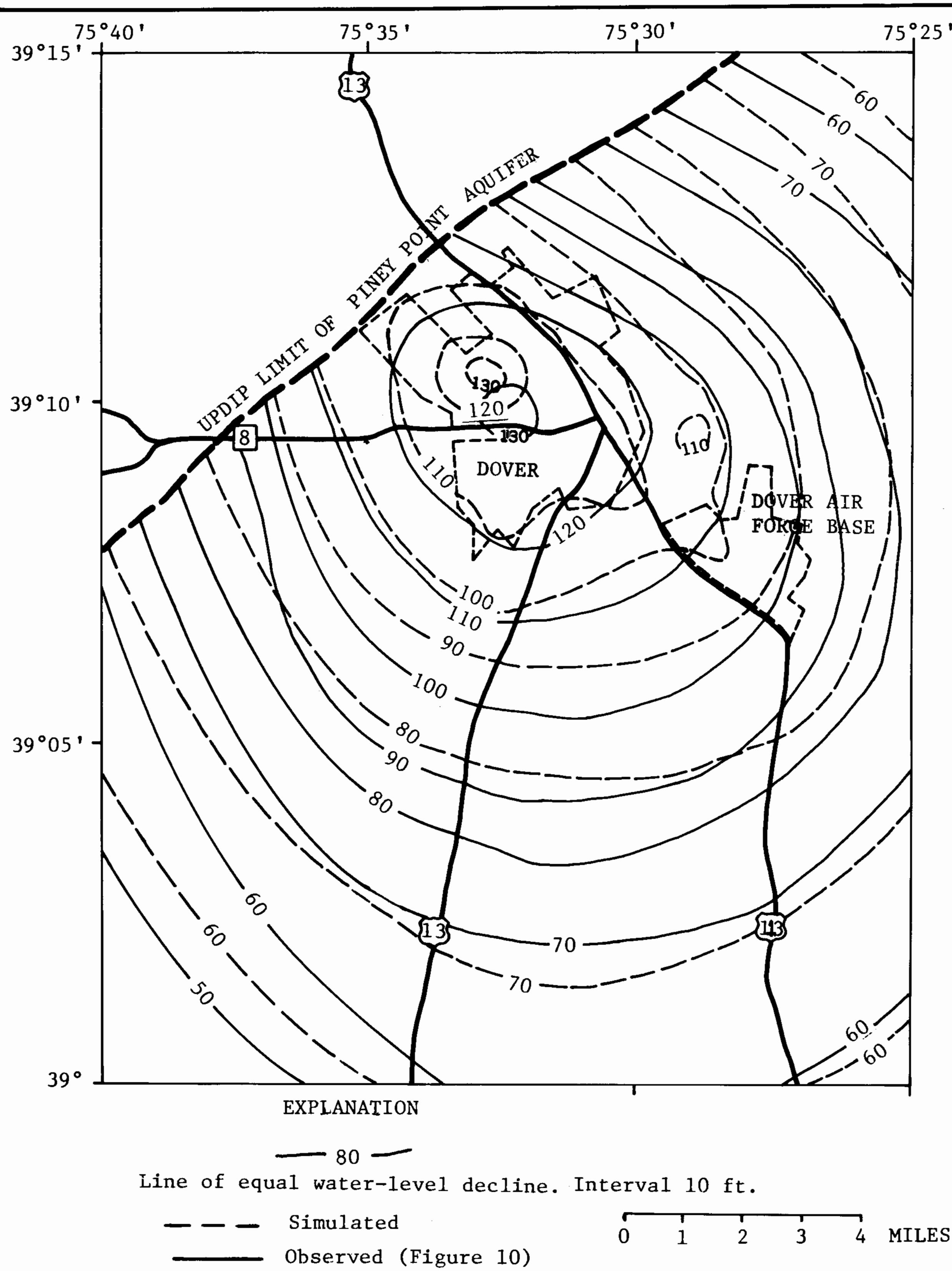
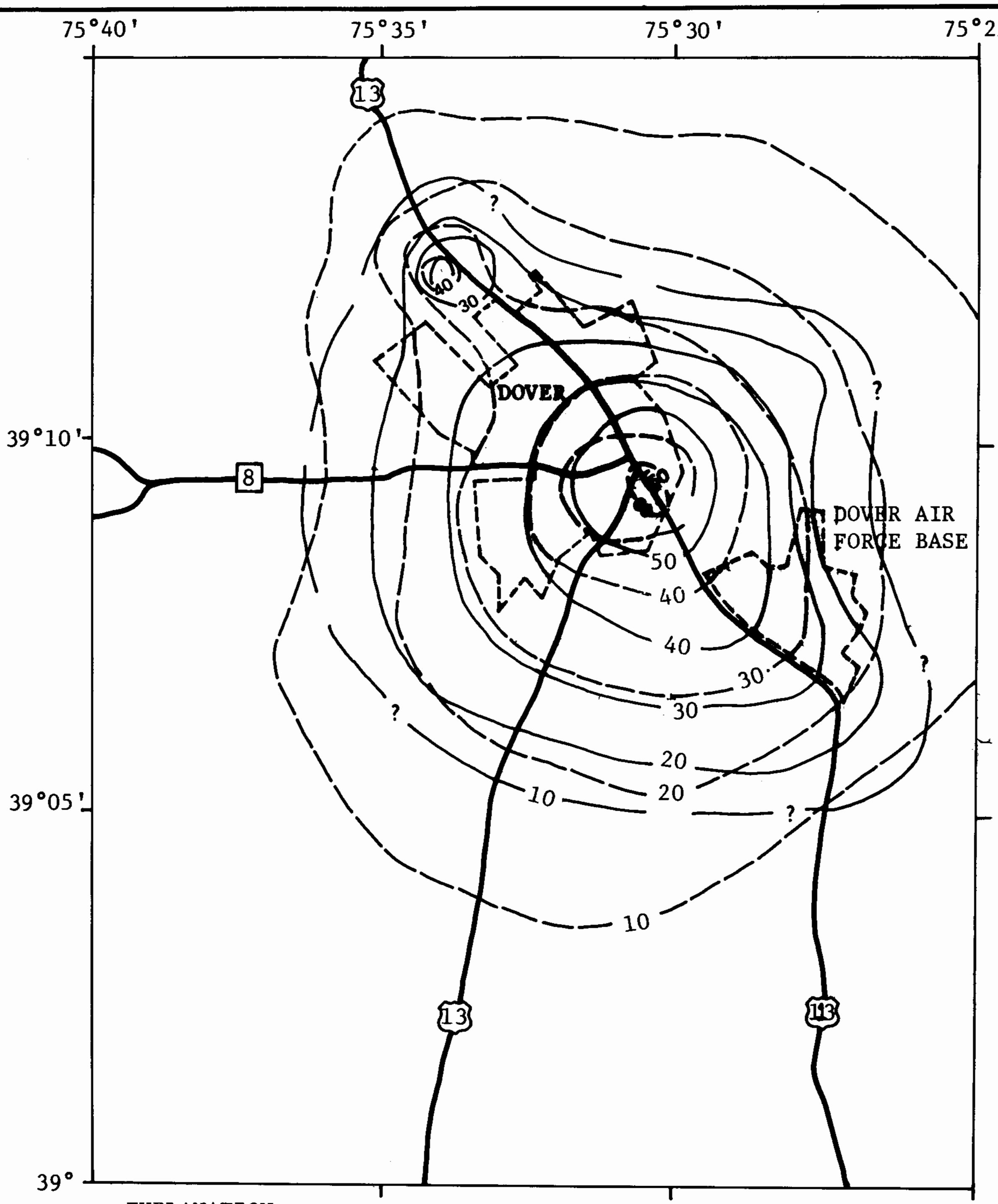


FIGURE 19 - SIMULATED AND OBSERVED HEAD DECLINES FOR THE PINEY POINT AQUIFER, 1952-77.



EXPLANATION

30

Line of equal water-level decline. Interval 10 ft.

? Approximately located

Simulated

Observed (Figure 15)

0 1 2 3 4 MILES

FIGURE 20 - SIMULATED AND OBSERVED HEAD DECLINES FOR THE CHESWOLD AQUIFER, 1952-77.

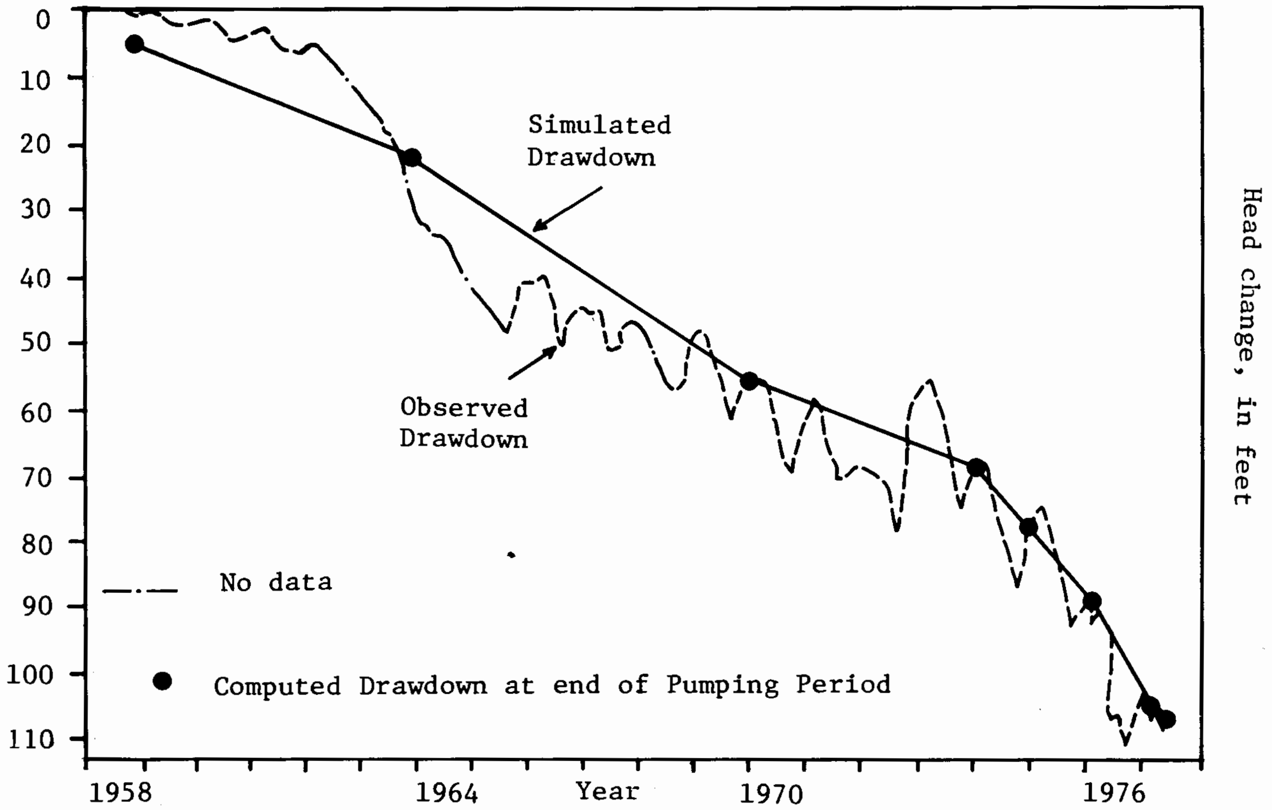


FIGURE 21 - OBSERVED AND SIMULATED HEAD CHANGES IN PINEY POINT AQUIFER OBSERVATION WELL Je32-4 (DOVER AIR FORCE BASE).

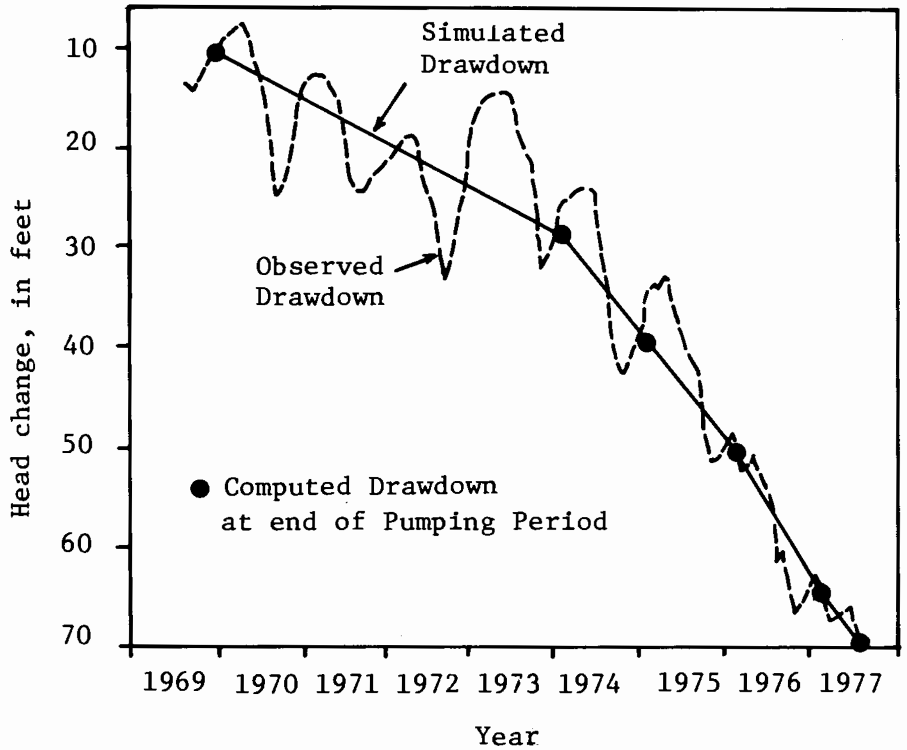


FIGURE 22 - OBSERVED AND SIMULATED HEAD CHANGES IN PINEY POINT AQUIFER OBSERVATION WELL Id55-1 (CITY OF DOVER, WHITE OAK ROAD).

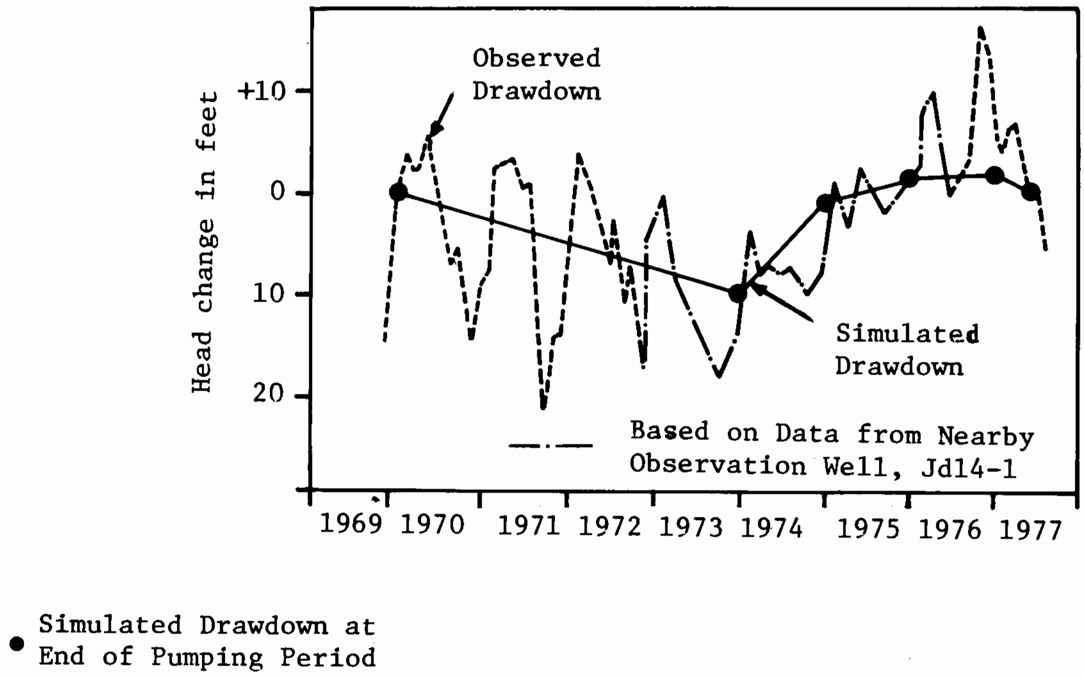


FIGURE 23 - OBSERVED & SIMULATED HEAD CHANGES IN CHESWOLD AQUIFER OBSERVATION WELL Id55-2 (CITY OF DOVER, WHITE OAK ROAD)

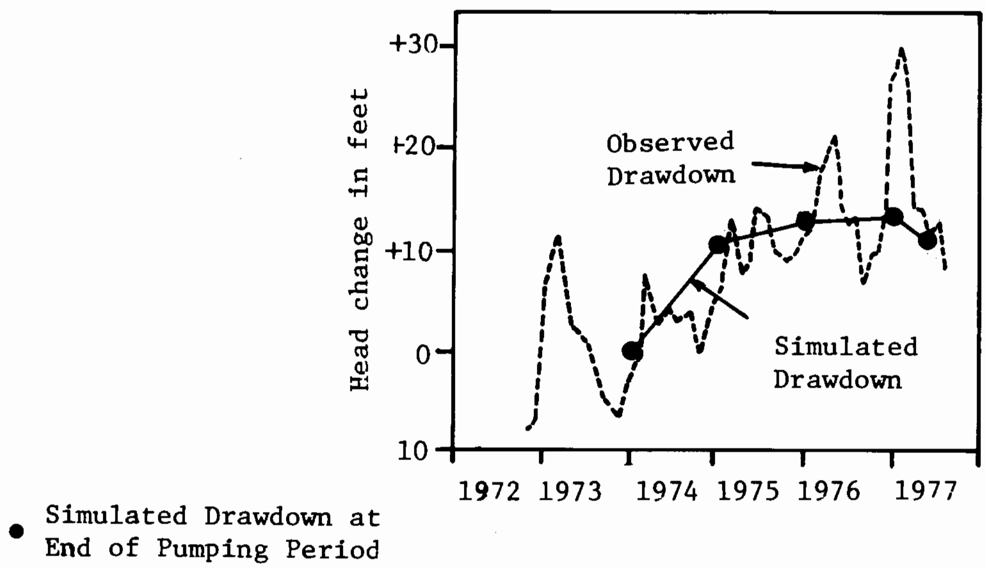


FIGURE 24 - OBSERVED AND SIMULATED HEAD CHANGES IN CHESWOLD AQUIFER OBSERVATION WELL Jd14-1 (CITY OF DOVER, DIVISION STREET).

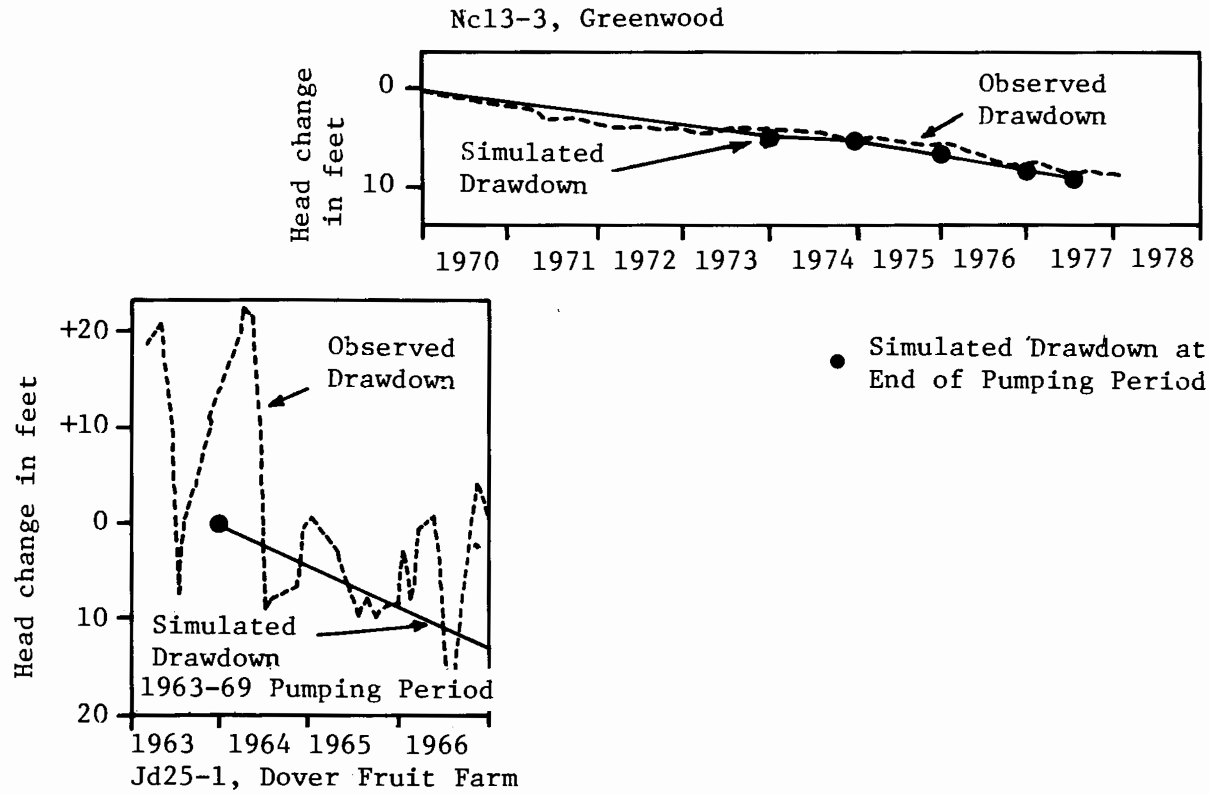


FIGURE 25 - OBSERVED AND SIMULATED HEAD CHANGES IN PINEY POINT AQUIFER OBSERVATION WELL Nc13-3 (GREENWOOD) AND IN CHESWOLD AQUIFER OBSERVATION WELL Jd25-1 (DOVER FRUIT FARM, DOVER).

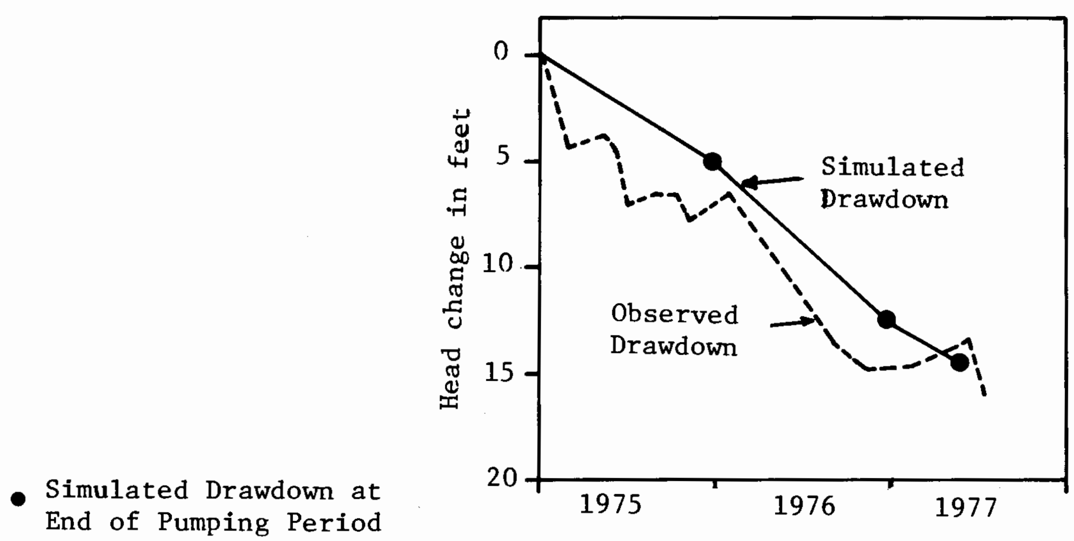
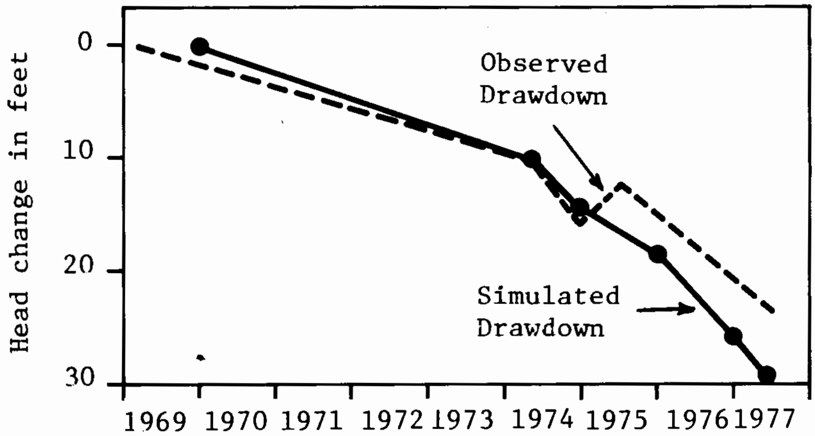
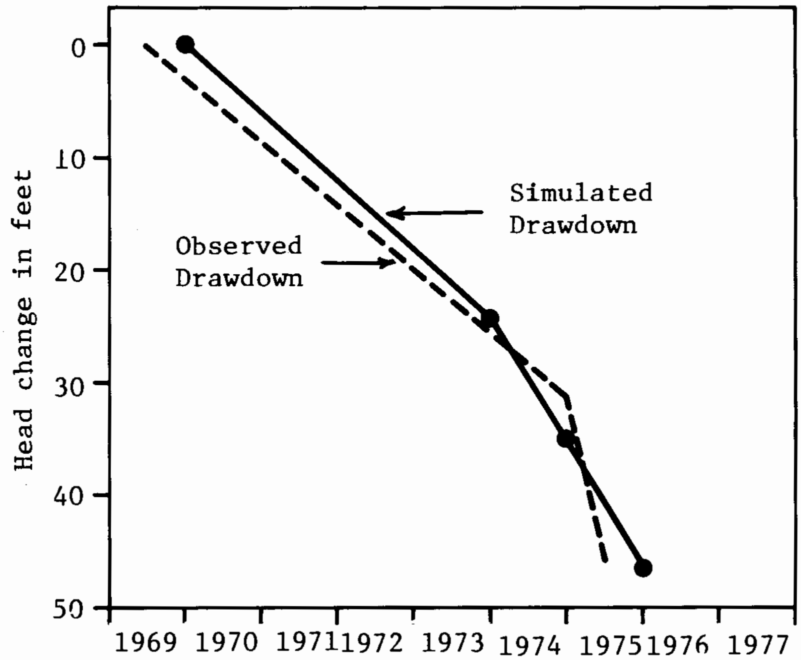


FIGURE 26 - OBSERVED AND SIMULATED HEAD CHANGES IN PINEY POINT AQUIFER OBSERVATION WELL Kc31-1 (PETERSBURG STATE FOREST).



He52-2, Bombay Hook Wildlife Refuge



Jd43-5, Camden-Wyoming

● Simulated drawdown at end of pumping period

FIGURE 27 - OBSERVED AND SIMULATED HEAD CHANGES IN PINEY POINT AQUIFER OBSERVATION WELLS He52-2 and Jd43-5.

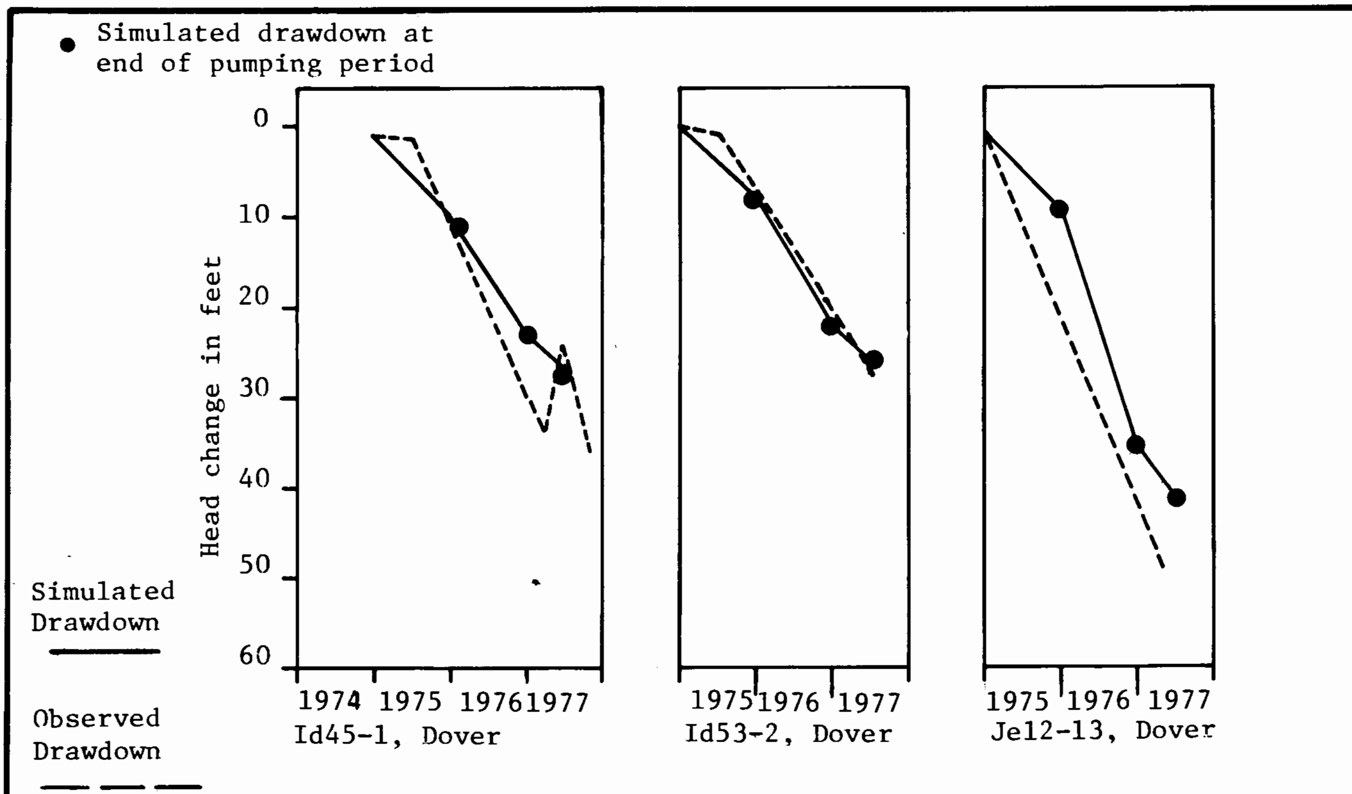


FIGURE 28 - OBSERVED AND SIMULATED HEAD CHANGES IN PINEY POINT AQUIFER OBSERVATION WELLS Id45-1, Id53-2, and Je12-13.

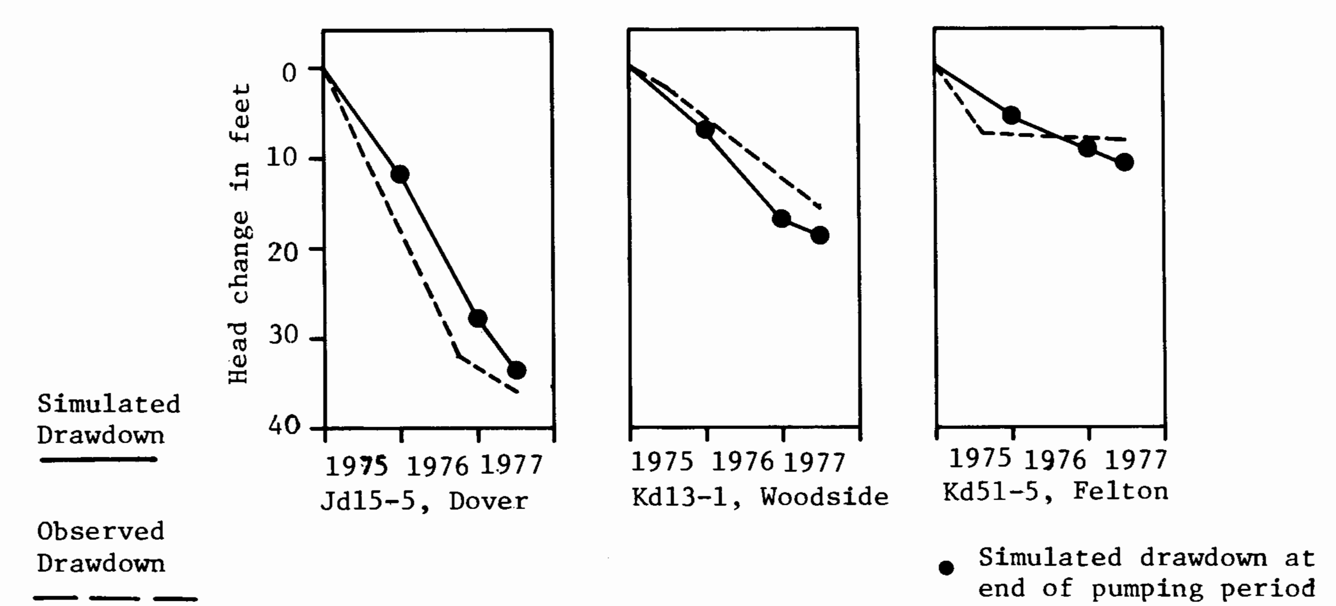


FIGURE 29 - OBSERVED AND SIMULATED HEAD CHANGES IN PINEY POINT AQUIFER OBSERVATION WELLS Jd15-3, Kd13-1, and Kd51-3.

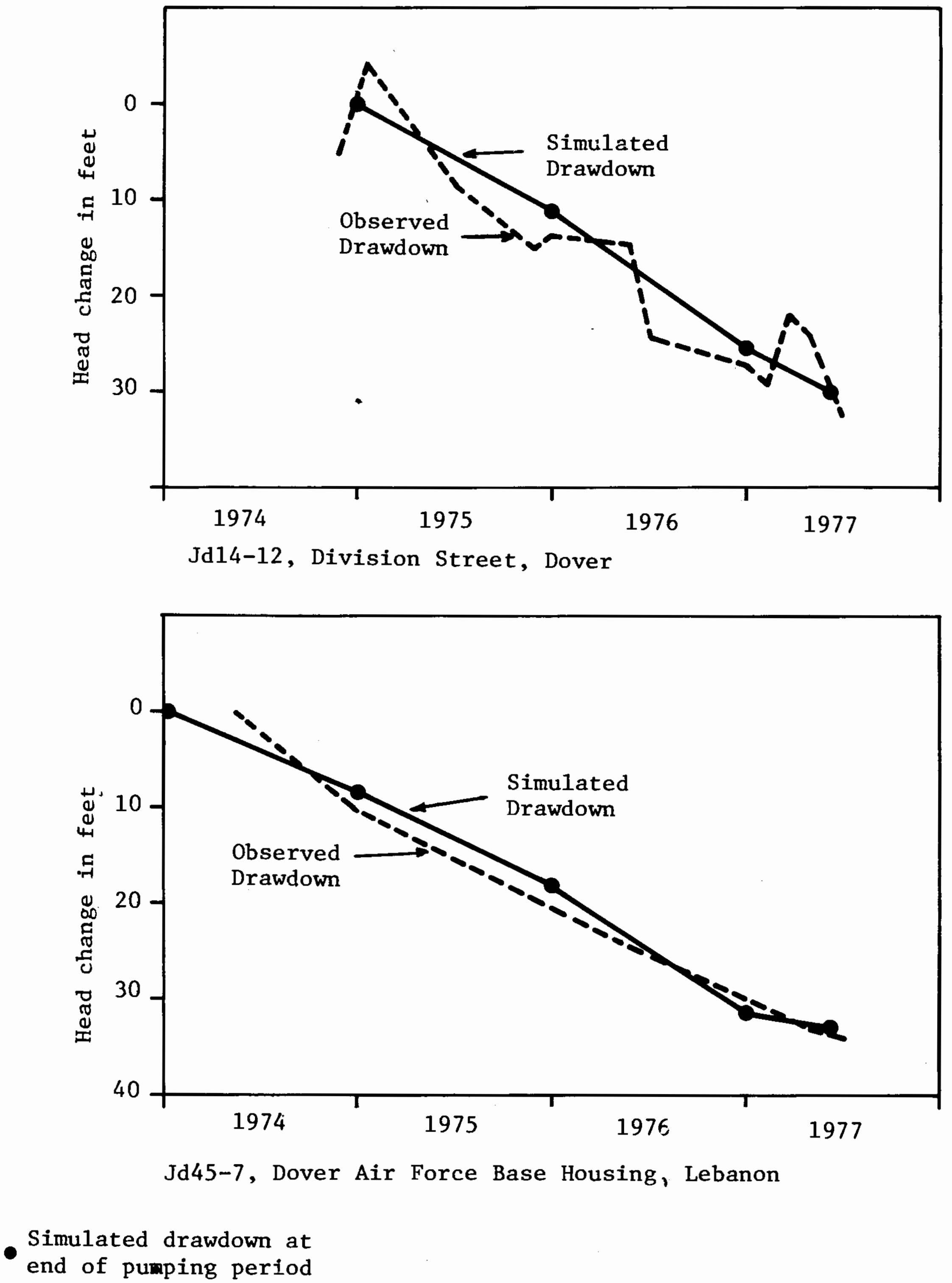


FIGURE 30 - OBSERVED AND SIMULATED HEAD CHANGES IN PINEY POINT AQUIFER OBSERVATION WELLS Jd14-12 and Jd45-7.

MODEL APPLICATION

The calibrated model of the aquifers underlying Kent County was used to evaluate the effects of future ground-water development. Three steady-state and one transient-state simulations using various pumpages were made to demonstrate the use of the model in evaluating head changes in the Piney Point and Cheswold aquifers. A transient simulation using 1977 pumpage was made to estimate the time required for the aquifers to reach equilibrium. The steady-state simulations were made for the following cases:

(1) The 1977 pumpage was simulated to determine the additional drawdown that would occur if combined withdrawals from the Piney Point and Cheswold aquifers were to stablilize at 8.6 Mgal/d.

(2) The 1974 pumpage was simulated for comparison with results of an identical simulation using a single-layer two-dimensional model of the Piney Point aquifer (Leahy, 1979a).

(3) A total pumpage of 16.6 Mgal/d was simulated with additional wells screened in both the Piney Point and Cheswold aquifers.

Projected water-level declines for the Piney Point aquifer in the study area are shown in Figure 31. These declines are the result of a steady-state simulation of the 1977 pumpage of 3.42 Mgal/d from the Piney Point aquifer and 5.17 Mgal/d from the Cheswold aquifer. Results of this simulation indicate that if ground-water withdrawals were to remain constant at the 1977 amount in both aquifers, water levels in the Piney Point aquifer are expected to decline approximately 20 feet below the June 1977 levels before reaching equilibrium. Water levels in the Cheswold aquifer would decline approximately 1 foot in the Dover area.

A transient-state simulation of a total of 9.3 years was made using 1977 pumpage to estimate the time required for the Piney Point and Cheswold aquifers to reach equilibrium. After simulating 4.7 years, or until February 1982, heads in the Piney Point aquifer in the Dover area were projected to decline approximately 14 feet below the June 1977 measured levels. The rate of decline at the end of the 4.7 years was about 1.5 feet per year (ft/yr). In the Cheswold aquifer, the projected decline was about 0.7 foot and the rate of decline was 0.08 ft/yr. After 9.3 years beyond June 1, 1977, or until October 1986, the projected head declines were about 18 feet in the Piney Point aquifer and 0.9 foot in the Cheswold aquifer. The approximate rate of head decline at the end of the 9.3-year period was 0.5 ft/yr in the Piney Point aquifer, and 0.04 ft/yr in the Cheswold aquifer.

Comparison of the results of the steady-state and transient-state simulations shows that after 4.7 years, projected water-level declines are about 70 percent of the projected steady-state declines in both the Piney Point and Cheswold aquifers. Also, at the end of the transient-state simulation (9.3 years or until October 1986), projected water-level declines were computed to be about 90 percent of the steady-state decline for both the Piney Point and Cheswold aquifers.

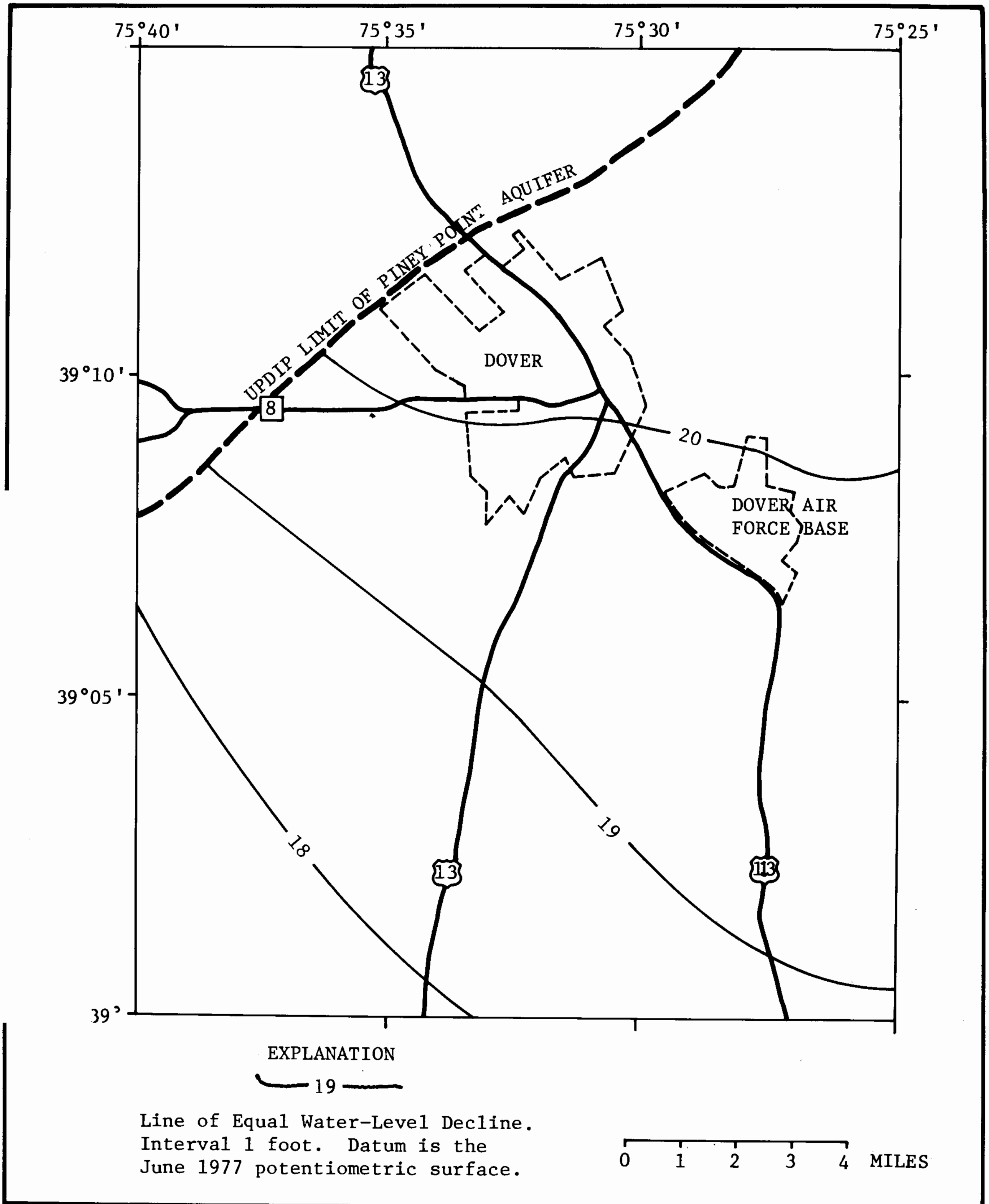


FIGURE 31 - PROJECTED HEAD DECLINES BELOW THE 1977 LEVEL FOR THE PINEY POINT AQUIFER RESULTING FROM A STEADY-STATE SIMULATION OF 1977 TOTAL WITHDRAWAL OF 8.6 Mgal/d (3.42 Mgal/d FROM THE PINEY POINT AQUIFER AND 5.17 Mgal/d FROM THE CHESWOLD AQUIFER).

Using the differences between the steady-state and transient-state predicted water-level declines and the rates of decline computed at the end of the 9.3-year simulation, the minimum time required for each aquifer to achieve steady-state equilibrium was estimated. In the Piney Point aquifer, the difference between the steady-state and transient-state water-level declines is approximately 2.5 feet. Using a rate of decline of 0.5 ft/yr, the Piney Point aquifer could be expected to reach steady-state equilibrium with the 1977 pumpage at the earliest, by 1991. Similarly, using the steady-state and transient-state water-level declines and the rate of decline, the Cheswold aquifer could be expected to reach equilibrium with the 1977 withdrawals at the earliest, by 1989. It should be emphasized, however, that these estimates are based on the assumption that water levels will continue to decline at the same rate computed by the model for October 1986. It is expected that the rate of decline will decrease with time. Therefore, the above estimated time represents the minimum time required for the system to reach equilibrium.

A steady-state simulation was made to compare the results of a two-dimensional, single-layer model of the Piney Point aquifer by Leahy (1979a) with the multilayer model. The purpose of the comparison was to illustrate the effects on model results caused by the use of a constant-head source bed for the Cheswold aquifer in the single-layer model. The pumpage simulated was 2.7 Mgal/d in both models and included the 1974 pumpage (Table 2) and an additional 0.2 Mgal/d for the Dover Air Force Base housing well. Head declines relative to the 1974 simulated heads in the Piney Point aquifer for both the multilayer and single-layer models are shown in Figure 32. The simulation using the single-layer model indicates head declines in the Dover area to be 12 feet below the 1974 measured potentiometric surface. In contrast, the multilayer model indicates a 24-foot head decline. The vertical hydraulic conductivity of the silty confining bed separating the Piney Point and Cheswold aquifers was slightly different in each of the models--3.0×10^{-5} ft/d in the single-layer model and 2.0×10^{-5} ft/d in the multilayer model. It is improbable that the slight difference in confining-bed conductivity would contribute the 12-foot difference in the simulated head declines in the Piney Point aquifer. The 12-foot difference in head decline suggests that the assumed constant head for the Cheswold aquifer used in the two-dimensional, single-layer model probably supplies an excessive amount of leakage to the Piney Point aquifer, thus, reducing the water-level declines. Comparison of these two different models illustrates the inaccuracies that can occur if the interactive nature of a multilayer aquifer system is ignored.

A steady-state simulation was made to evaluate the response of the model to a pumpage of 16.6 Mgal/d, or nearly double the 1977 pumpage. The increase in pumpage was divided between the Piney Point and Cheswold aquifers. Hypothetical well fields were located in the model a few miles south of Dover where increased water demands are expected. Pumpage from the Cheswold aquifer was increased 4.0 Mgal/d by the addition of one new production well and six hypothetical wells (Figure 33 and Table 5). Pumpage from the Piney Point aquifer was increased 3.8 Mgal/d with the addition of six hypothetical wells [wells 3, 5, 6, 7, 8, 9 (Figure 34 and Table 5)], and with a net increase of 0.2 Mgal/d from three existing wells in the City of Dover [wells 1, 2, and 4 (Figure 34 and Table 5)].

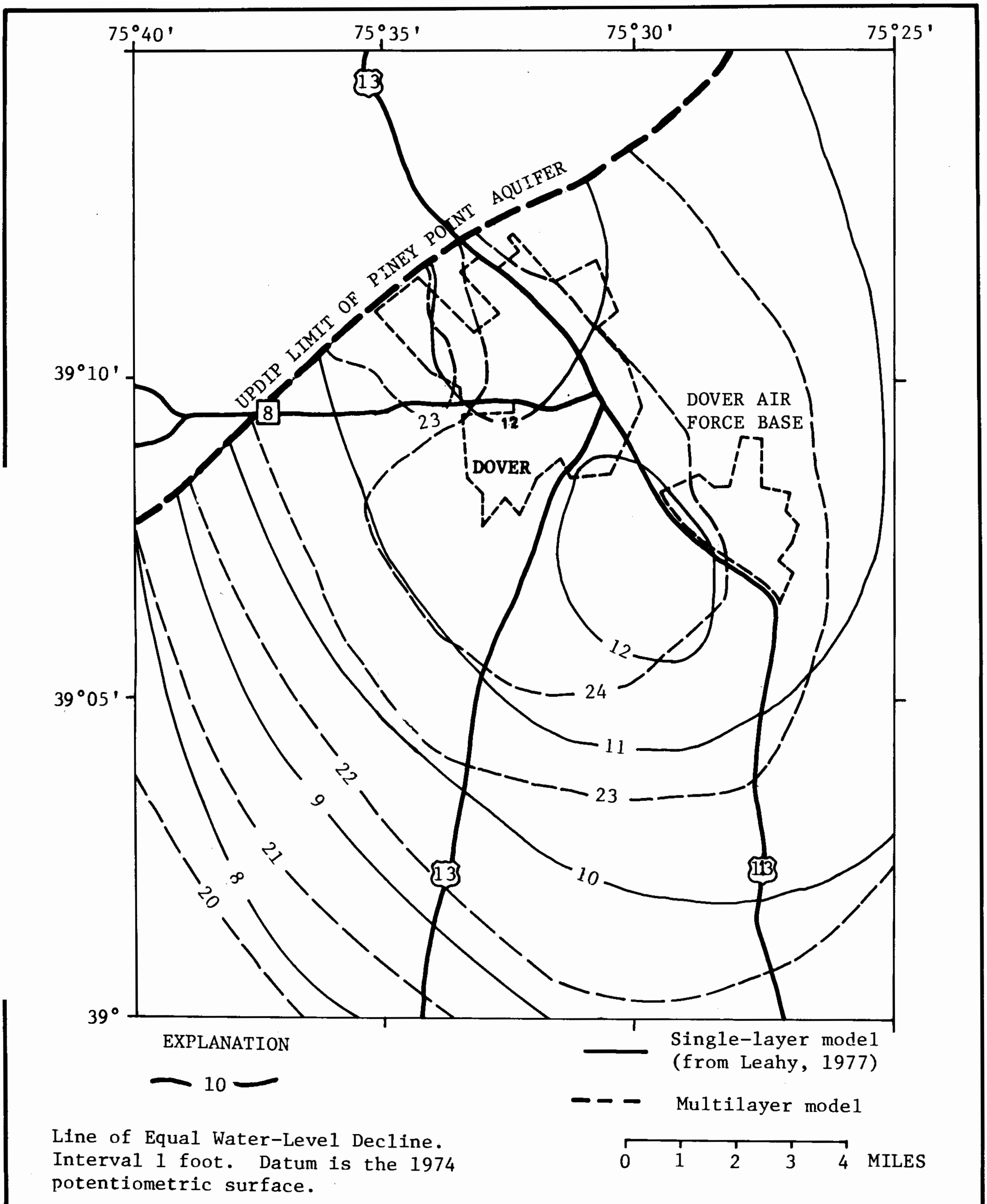
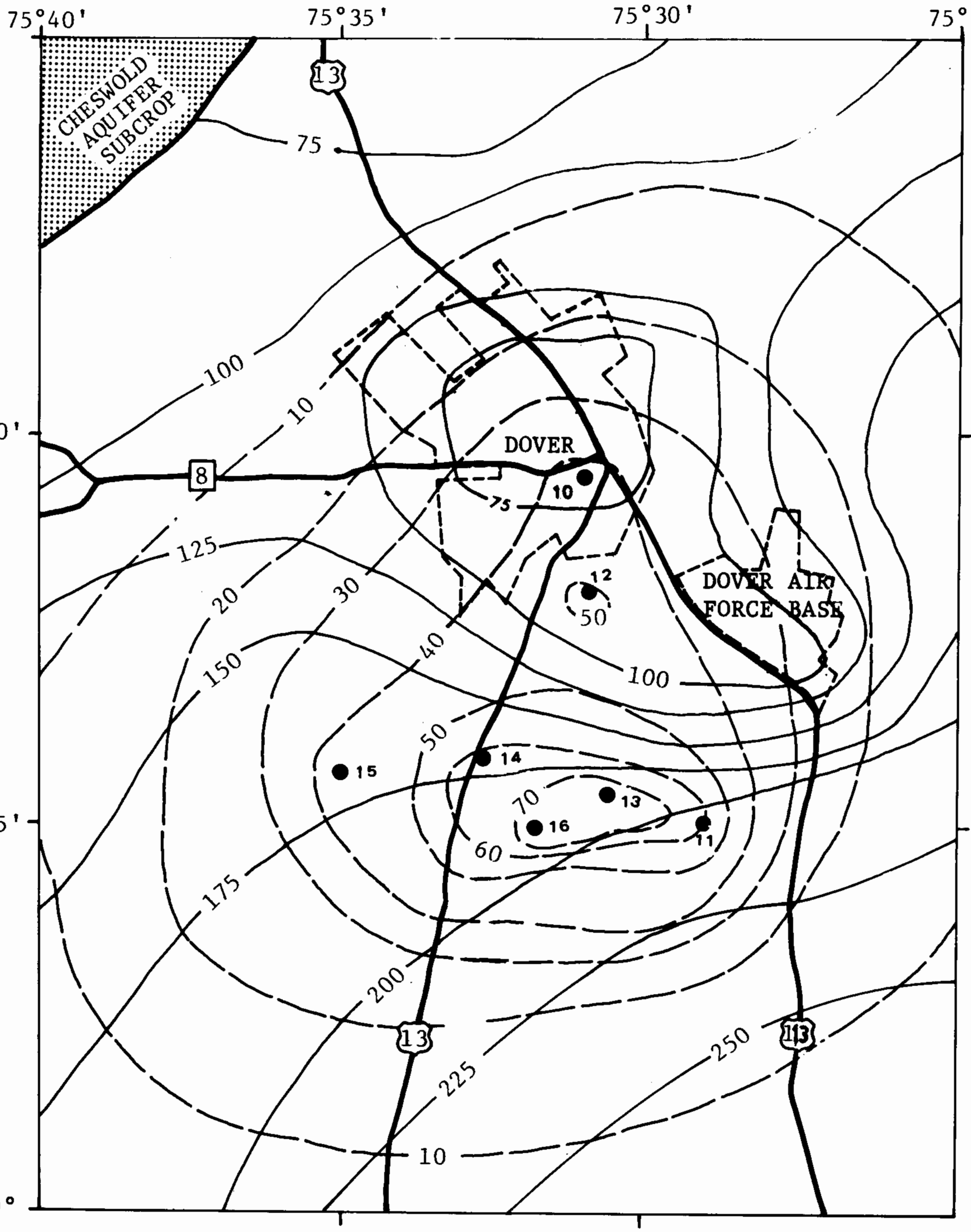


FIGURE 32 - COMPARISON OF PROJECTED HEAD DECLINES BELOW THE 1974 LEVEL OF 1974 PUMPAGE FOR THE PINEY POINT AQUIFER RESULTING FROM STEADY-STATE SIMULATIONS USING MULTILAYER AND SINGLE-LAYER MODELS.

The location and pumping rates of the hypothetical wells were somewhat arbitrary. However, wells were placed in areas of probable increasing water demands. Experiments were not made to determine the optimum well spacing and yields for each aquifer in the system; however, pumping rates were gradually increased at the hypothetical well sites until a maximum reasonable water-level decline (relative to the June 1977 potentiometric surface) was reached that was above the top of the aquifers.

Figures 33 and 34 show the available drawdown in 1977 and the projected head declines below the 1977 potentiometric surface due to the pumpage of 16.6 Mgal/d. Because of the accompanying reduction in transmissivity and the possible collapse of well screens, it is generally considered undesirable to lower water levels below the top of a confined aquifer. Therefore, available drawdown can be defined as the difference between the 1977 potentiometric surface and the top of the aquifer. In the Piney Point aquifer, a maximum decline at model nodes of 162.5 feet was projected in the Voshell Pond area, south of Dover. In the Cheswold aquifer, a maximum decline of 75.7 feet was projected in the Brown's Corner area. A comparison between the available drawdowns and the projected head declines in both aquifers indicates the aquifers can sustain the simulated pumpage without fear of exceeding the available drawdown.

The water-level declines shown in Figures 33 and 34 represent the mean declines within a finite-difference block (Figure 2). However, it is also possible to project the water-level decline in a pumping well. This is calculated by a modified Theim equation (Trescott, Pinder, and Larson, 1976). Table 5 shows projected water-level declines at pumping wells selected because of their location and large pumpage. In the calculation, all wells were assumed to have 12-inch-diameter screens and negligible losses due to well construction. Comparing the drawdowns in wells with the available drawdown indicates that a total withdrawal of 16.6 Mgal/d could be obtained without having heads fall below the top of the aquifer in most of the wells. At a few sites, however, projected drawdowns are very close to, or have slightly exceeded the available drawdown. The pumping rate would probably have to be reduced at these sites to avoid dewatering the aquifer. The reductions could probably be offset by increases in the pumping rate at other sites or by adding additional wells in areas that have more available drawdown.



—125—

Line of Equal Available Drawdown Interval 25 ft. The available drawdown is the difference between the June 1977 potentiometric surface and the top of the aquifer.

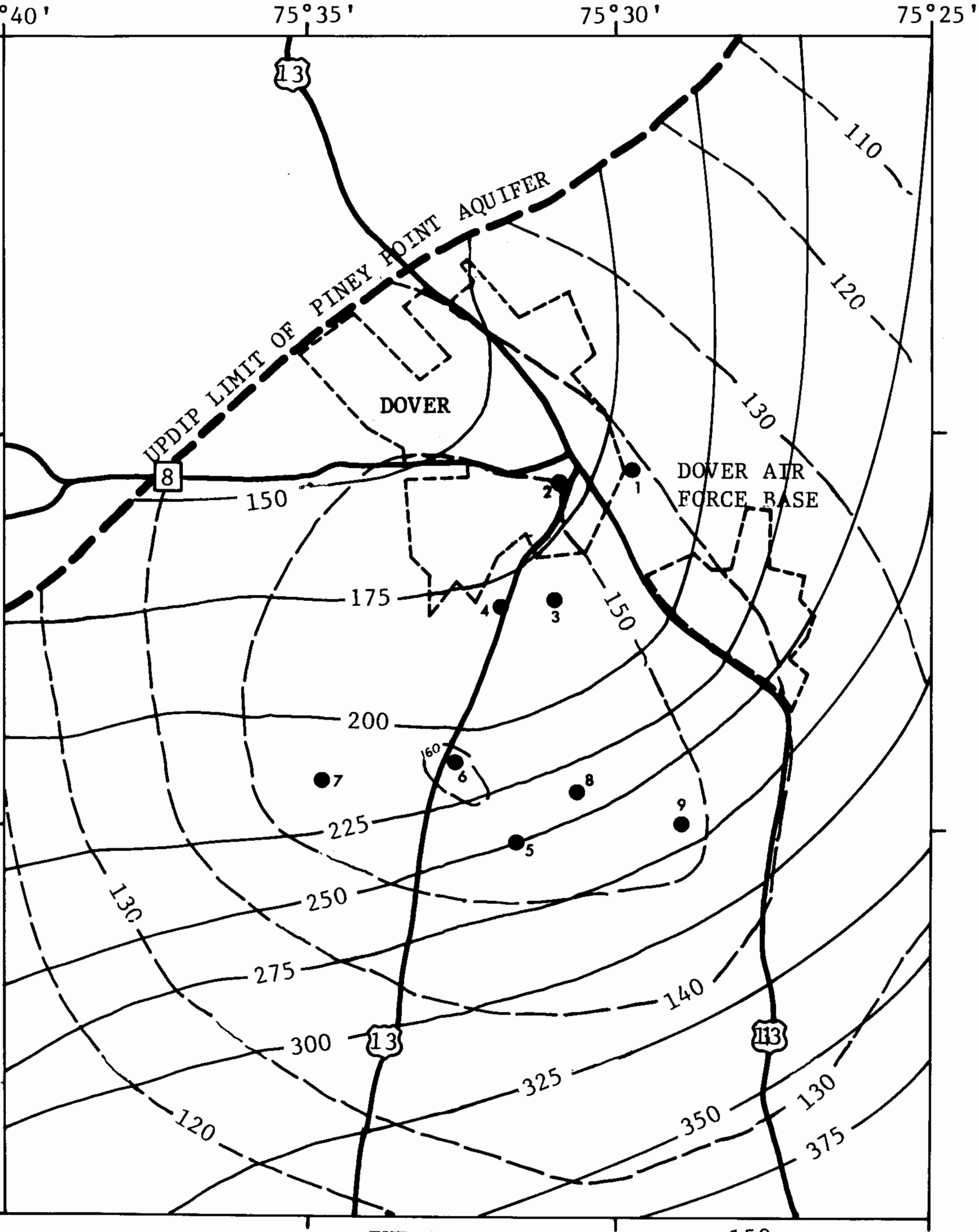
— — 10 — —

Line of Equal Water-Level Decline Interval 10 ft. Datum is the June 1977 potentiometric surface.

0 1 2 3 4 MILES

● 10 :Pumping well. See Table 5.

FIGURE 33 - PROJECTED HEAD DECLINES BELOW THE 1977 LEVEL FOR THE CHESWOLD AQUIFER RESULTING FROM A STEADY-STATE SIMULATION OF A TOTAL WITHDRAWAL OF 16.6 Mgal/d (7.41 Mgal/d FROM THE PINEY POINT AND 9.15 Mgal/d FROM THE CHESWOLD).



Line of Equal Available Drawdown. Interval 25 feet. The available drawdown is the difference between the June 1977 potentiometric surface and the top of the aquifer.

Line of Equal Water-Level Decline. Interval 10 ft. Datum is the June 1977 potentiometric surface.

0 1 2 3 4 MILES

10: Pumping well. See Table 5.

FIGURE 34 - PROJECTED HEAD DECLINES BELOW THE 1977 LEVEL FOR THE PINEY POINT AQUIFER RESULTING FROM A STEADY-STATE SIMULATION OF A TOTAL WITHDRAWAL OF 16.6 Mgal/d (7.41 Mgal/d FROM THE PINEY POINT AND 9.15 Mgal/d FROM THE CHESWOLD).

Table 5.—Pumping rates other than 1977 rates used in simulation of withdrawal of 16.6 Mgal/d, and projected drawdowns at the wells.

Well No. (Figs. 33 & 34)	Location of well or hypothetical well	Continuous pumping rates (Mgal/d)	Continuous pumping rates (gal/min)	Projected drawdown at pumping well (ft below June 1977 water level)	Approximate available drawdown in June 1977 (ft)
		PINEY POINT AQUIFER			
1	Horsepond Rd., Dover 1/	0.58	400	156.0	190
2	Treatment Plant, Dover 2/	.49	340	175.7	173
3	Moore's Lake	.58	400	178.9	195
4	Rodney Village, Dover 3/	.37	260	174.1	190
5	Woodside	.65	450	175.6	250
6	Voshell Pond	.65	450	186.5	210
7	Derby Pond	.65	450	182.8	215
8	Brown's Corner	.65	450	170.0	240
9	Magnolia	.65	450	166.5	270
		CHESWOLD AQUIFER			
10	Treatment Plant, Dover 4/	.66	460	61.2	70
11	Magnolia	.32	225	206.2	210
12	Moore's Lake	.66	460	84.6	90
13	Brown's Corner	.58	405	137.6	180
14	Voshell Pond	.58	405	111.5	170
15	Derby Pond	.58	405	86.7	165
16	Woodside	.58	405	126.3	190
		5/9.24	6,415		

1 Existing production well. (1977 pumping rate reduced approximately 90 gal/min.)

2 Existing production well. (1977 pumping rate increased approximately 90 gal/min.)

3 Existing production well. (1977 pumping rate increased approximately 120 gal/min.)

4 Pumping began in this production well in 1978. Estimate of 460 gal/min included in this simulation.

5 Additional pumpage of 7.36 Mgal/d used in this simulation was the 1977 pumpage (Table 2) that was assumed to have remained constant, except as noted above.

SUMMARY AND CONCLUSIONS

A quasi three-dimensional model was constructed to simulate the response of the Piney Point and Cheswold aquifers to pumping. Calibration of the model resulted in (1) refinement of the transmissivity distribution of the Cheswold aquifer, (2) refinement of the hydraulic properties of confining beds adjacent to this aquifer, and (3) increased confidence in the transmissivity distribution of the Piney Point aquifer used by Leahy (1979a). The calibrated model was used to project the response of the aquifer system to possible future trends in ground-water withdrawals from the Piney Point and Cheswold aquifers. With proper precautions the model can also be used by ground-water planners for evaluating the effects of increased pumpage in either the Piney Point or Cheswold aquifers.

Results of calibration of the model are summarized as follows:

(1) Transmissivity of the Piney Point aquifer ranged from 7,350 ft^2/d, near Lebanon, Delaware, to effectively zero at the boundaries of the aquifer (Figure 7). The storage coefficient was 3.0×10^{-4}.

(2) Transmissivity of the Cheswold aquifer ranged from 7,400 ft^2/d to less than 1,000 ft^2/d in the Dover area (Figure 8). The storage coefficient was 1.4×10^{-4}.

(3) Vertical hydraulic conductivity of the silty confining bed separating the Piney Point and Cheswold aquifers was 2.0×10^{-5} ft/d. The vertical conductivity of the sandy confining bed separating the Cheswold and unconfined aquifers ranged from 4.0×10^{-4} ft/d to 1.2×10^{-3} ft/d. Specific storage used for all the confining beds was 1.0×10^{-6} ft^{-1}.

(4) An area of substantial vertical leakage from the unconfined aquifer to the Cheswold aquifer was confirmed.

The calibrated model was used to project water-level declines resulting from withdrawals from the Piney Point and Cheswold aquifers. A steady-state simulation of 16.6 Mgal/d, or almost double the 1977 total pumpage, produced maximum declines at model nodes below the 1977 potentiometric surfaces of 162.5 feet for the Piney Point aquifer, and 75.7 feet for the Cheswold aquifer. Pumping levels were calculated for selected well sites; these levels were generally above the tops of the aquifers.

A steady-state simulation using the 1974 pumpage was made for comparison of projected declines in the Piney Point aquifer with the results of a previous study by Leahy (1979a), which used a two-dimensional single-layer model to represent the Piney Point aquifer. Unlike the earlier single-layer model of Leahy (1979a), the multilayer model used in this study considered head changes in the overlying Cheswold aquifer and a leaky confining bed underlying the Piney Point aquifer. Water-level declines using the single-layer model of the Piney Point aquifer were about 12 feet less than the declines projected by the multilayer model. This difference indicates the inaccuracies that can occur in model results when unrealistic boundary conditions (constant head) are used to represent an adjacent aquifer, and also justifies the need for a multilayer model of this interactive aquifer system.

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APPENDIX I

Conversion of Measurement Units

Factors for converting inch-pound units to metric (SI) units are shown to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the inch-pound units.

Inch-pound unit	Multiply by	Metric unit
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
million gallons per day (Mgal/d)	3785	cubic meters per day (m^3/d)
mile (mi)	1.609	kilometer (km)
per foot (/ft)	3.281	per meter (/m)
square mile (mi)	2.590	square kilometer (km)

Note Regarding Vertical Datum

The National Geodetic Vertical Datum of 1929, the reference surface to which relief features and altitude data are related, and formerly called "mean sea level," is referred to as "sea level" throughout this report.

APPENDIX II

Table 2.--Average daily pumpage by well for the Piney Point and Cheswold aquifers in Delaware from pre-1952 to 1977.

WELL NUMBER	NAME AND LOCATION	DURATION OF PUMPING	Average Daily Pumpage (Mgal/d)								
			PRE-1952 ESTIMATES	1952-1958	1959-1963	1964-1969	1970-1973	1974	1975	1976	1977
PINEY POINT AQUIFER											
Id53-2,3	McKee Run Generating Plant City of Dover	[1]1962 - 1977	0.000	0.000	[2]0.359	0.381	0.374	[3]0.357	0.323	0.319	0.326
Jd12-3	Dover Country Club Dover	1970 - 1976	0.000	0.000	0.000	0.000	[2]0.023	[2]0.031	[2]0.031	0.028	0.000
Jd14-15	Treatment Plant City of Dover	1970 - 1977	0.000	0.000	0.000	0.000	0.117	[3]0.212	0.297	0.202	0.317
Jd23-1	Crossgates City of Dover	1966 - 1977	0.000	0.000	0.000	0.060	0.156	[3]0.252	0.327	0.208	0.323
Jd25-3	Danner Farm City of Dover	1965 - 1977	0.000	0.000	0.000	0.076	0.209	[3]0.339	0.402	0.334	0.531
Jd34-1	Rodney Village City of Dover	1970 - 1977	0.000	0.000	0.000	0.000	0.144	[3]0.268	0.425	0.734	0.250
Jd42-2	Wyoming Ice Company Wyoming	1947 - 1977	0.060	[2]0.060	[2]0.060	[2]0.060	[2]0.060	[2]0.060	[2]0.060	[2]0.060	[2]0.060
Jd43-5	Camden-Wyoming Water Authority Camden-Wyoming	1969 - 1977	0.000	0.000	0.000	0.000	[2]0.200	[2]0.200	[2]0.320	[2]0.320	[2]0.320
Jd45-7	Dover Air Force Base Housing Lebanon	1975 - 1977	0.000	0.000	0.000	0.000	0.000	0.000	0.043	0.099	0.119
Je12-13	Horsepond Road City of Dover	1975 - 1977	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.624	0.710
Jc32-5	Dover Air Force Base near Dover	1963 - 1977	0.000	0.000	0.084	0.676	0.442	0.523	0.468	0.471	0.448
Kd11-8	Woodside	1959 - 1974	0.000	0.000	[2]0.076	[2]0.085	[2]0.077	[2]0.052	0.000	0.000	0.000
Kd13-1	Kent County Vocational Technical High School, Woodside	1965 - 1977	0.000	0.000	0.000	[2]0.009	[2]0.011	[2]0.011	[2]0.011	[2]0.011	[2]0.011
Kd51-5	Felton, Del.	1960 - 1977	0.000	0.000	[2]0.127	[2]0.160	[2]0.160	[2]0.160	[2]0.100	[2]0.050	0.000
		Total pumpage	0.06	0.06	0.71	0.51	0.97	2.47	2.83	3.46	3.42

1 Id53-2 removed from service in 1969.

2 Estimated pumpage.

3 Discrepancy with pumpage reported by Leahy (1979) caused by 10-month average used in the earlier study versus 12-month average used in this study.

Table 2.--Average daily pumpage by well for the Piney Point and Cheswold aquifers in Delaware from pre-1952 to 1977--Continued.

WELL NUMBER	NAME AND LOCATION	DURATION OF PUMPING	Average Daily Pumpage (Mgal/d)								
			PRE-1952 ESTIMATES	1952-1958	1959-1963	1964-1969	1970-1973	1974	1975	1976	1977
CHESWOLD AQUIFER											
Ic25-10	C. Boggs[4], Cheswold	1975 - 1977	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.006	0.008
Id32-8[5]	Reichold Chemical Corp., Dover	1957 - 1977	0.000	0.121	0.425	0.432	0.401	0.409	0.326	0.471	0.471
Id42-5,6	Kentwood Mobile Estates, Dover	1964 - 1977	0.000	0.000	0.000	[2]0.042	[2]0.042	[2]0.042	[2]0.042	[2]0.042	[2]0.042
Id43-4,5,6	Delaware State College, Dover	1927 - 1977	0.050	[2]0.075	[2]0.075	0.077	0.097	0.127	0.127	0.127	0.127
Jd14-1	Division Street, City of Dover	1938 - 1977	0.200	[2]0.215	[2]0.270	0.245	0.129	0.000	0.000	0.000	0.000
Jd14-2	Old Power Plant, City of Dover	1932 - 1977	0.600	[2]0.215	[2]0.270	0.330	0.520	0.374	0.349	0.346	0.308
Id14-5	Richardson - Robbins, Dover	1931 - 1974	0.100	0.110	0.110	0.135	0.140	0.071	0.000	0.000	0.000
Jd14-6	Water Street, City of Dover	1952 - 1977	0.000	[2]0.215	[2]0.270	0.453	0.520	0.514	0.530	0.433	0.532
Jd14-7	Farmer's Bank, Dover	1952 - 1977	0.000	[2]0.007	[2]0.007	[2]0.007	[2]0.008	[2]0.008	[2]0.008	[2]0.008	[2]0.008
Jd14-11,15-1	Playtex Corporation, Dover	1948 - 1977	0.500	0.900	0.900	0.876	0.839	0.851	0.828	0.828	0.828
Jd15-2	Bayard Avenue, City of Dover	1955 - 1977	0.000	0.111	[2]0.270	0.247	0.578	0.718	0.714	0.544	0.724
Jd15-4	East Dover Elementary School City of Dover	1964 - 1977	0.000	0.000	0.000	0.545	0.475	0.359	0.560	0.592	0.592
Jd24-1	Dover Street, City of Dover	1948 - 1977	0.200	[2]0.215	[2]0.270	0.447	0.551	0.434	0.467	0.493	0.591

2 Estimated pumpage.

4 Water used by Pittsburgh Paint and Glass Corp., Cheswold.

5 The pumpage is the sum of all wells constructed in the Cheswold aquifer.

Table 2.--Average daily pumpage by well for the Piney Point and Cheswold aquifers in Delaware from pre-1952 to 1977--Continued.

WELL NUMBER	NAME AND LOCATION	DURATION OF PUMPING	Average Daily Pumpage (Mgal/d)								
			PRE-1952 ESTIMATES	1952-1958	1959-1963	1964-1969	1970-1973	1974	1975	1976	1977
			CHESWOLD AQUIFER--Continued								
Jd25-2	Danner Farm, City of Dover	1964 - 1976	0.000	0.000	0.000	0.382	0.275	0.222	0.085	0.118	0.000
Jd35-[6]	Lakeland Inc., near Dover	1960 - 1977	0.000	0.000	[2]0.019	[2]0.023	[2]0.023	[2]0.023	[2]0.023	[2]0.023	[2]0.023
Jd42-11	Wyoming Block Inc., Wyoming	1963 - 1977	0.000	0.000	0.000	[2]0.003	[2]0.007	[2]0.007	[2]0.007	[2]0.007	[2]0.007
Jd43-2	Camden-Wyoming Water Authority Camden-Wyoming	1952 - 1974	0.000	[2]0.139	[2]0.158	[2]0.262	[2]0.120	[2]0.120	0.000	0.000	0.000
Jd43-3	Camden Park Water Company Camden-Wyoming	1955 - 1977	0.000	[2]0.034	[2]0.060	[2]0.060	[2]0.060	[2]0.060	[2]0.060	[2]0.060	[2]0.060
Jd44-28	Tidewater Utilities Royal Grant Development near Camden-Wyoming	1975 - 1977	0.000	0.000	0.000	0.000	0.000	0.000	[2]0.008	[2]0.008	[2]0.008
Je14-2	Village Inn, Little Creek	1975 - 1977	0.000	0.000	0.000	0.000	0.000	0.000	[2]0.002	[2]0.002	[2]0.002
Je21-2	Kings Cliff Trailer Court Dover	1954 - 1977	0.000	[2]0.017	[2]0.024	[2]0.024	[2]0.024	[2]0.024	[2]0.024	[2]0.024	[2]0.024
Je31-1	Dover Air Force Base "B" well near Dover [7]	1953 - 1977	0.250	0.433	0.483	0.336	0.457	0.395	0.249	0.333	0.258
Je31-2	Dover Air Force Base "C" well near Dover	1955 - 1977	0.000	0.206	0.409	0.274	0.358	0.246	0.315	0.307	0.284
Je31-5	Tidewater Utilities General's Green Development near Dover	1977 - 1977	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	[2]0.008
Je32-3	Dover Air Force Base "A" well near Dover [7]	1952 - 1977	0.250	0.433	0.407	0.268	0.301	0.298	0.227	0.192	0.245
Je42-2	George Concrete Co., near Dover	1962 - 1977	0.000	0.000	0.000	[2]0.002	[2]0.002	[2]0.002	[2]0.002	[2]0.002	[2]0.002
Jf41-2	Kitts Hummock Assn., Kitts Hummock	1961 - 1977	0.000	0.000	[2]0.012	[2]0.021	[2]0.021	[2]0.021	[2]0.021	[2]0.021	[2]0.021
		Total Pumpage	2.15	3.45	4.44	5.49	5.95	5.33	4.98	4.99	5.17
Total combined Piney Point and Cheswold Aquifer Pumpage			2.21	3.51	5.15	7.00	7.92	7.80	7.81	8.45	8.59

[2]Estimated pumpage.

[6]Wells at the site have not been numbered.

[7]Several unnumbered wells drilled in the early 1940's were used for the pre-1952 estimate.

Table 3. Transmissivities and Coefficients of Storage for the Piney Point and Cheswold Aquifers as Determined by Aquifer Tests in Kent and Sussex Counties, Delaware and Caroline County, Maryland.

WELL NUMBER	DATE OF TEST	NAME AND LOCATION	ANALYSIS BY	METHOD OF ANALYSIS	TRANSMISSIVITY (ft^2/d)	COEFFICIENT OF STORAGE	DURATION OF TEST
		PINEY POINT AQUIFER					
Id53-2	4-4-62	McKee Run Generating Plant #6 City of Dover	R. W. Sundstrom	Theis Recovery	800		21 Hours
Id53-3	4-4-62	McKee Run Generating Plant #7 City of Dover	R. W. Sundstrom	Theis Recovery	1140		21 Hours
Jd14-12	10-19-61	Division Street City of Dover	R. W. Sundstrom	Theis Recovery	3200		5 Hours
Jd23-1	8-2-65	Crossgates City of Dover	R. W. Sundstrom	Theis Recovery	2800		1 Day
Jd25-4	5-16-75	Danner Farm City of Dover	P. P. Leahy	Hantush Modified Leaky Artesian	4100	2.8×10^{-4}	23 Days
Jd34-1	1-2-69	Rodney Village City of Dover	R. H. Johnston	Theis non-leaky Artesian	3300		1 Day
Jd45-5	5-1-74	Dover Air Force Base Housing	R. H. Johnston and P. P. Leahy	Theis non-leaky Artesian	7350	3×10^{-4}	1 Day
Je12-13	7-22-75	Horsepond Road City of Dover	R. H. Johnston and P. P. Leahy	Theis Recovery	4000		2 Hours

Table 3. Continued

WELL NUMBER	DATE OF TEST	NAME AND LOCATION	ANALYSIS BY	METHOD OF ANALYSIS	TRANSMISSIVITY (ft^2/d)	COEFFICIENT OF STORAGE	DURATION OF TEST
			PINEY POINT AQUIFER				
Je32-4	7-24-63	Dover Air Force Base	R. D. Varrin and R. W. Sundstrom	Theis non-leaky Artesian	4300 to 5350	3×10^{-4}	Several Hours
Kd11-8	3-11-59	Woodside	R. W. Sundstrom	Theis Recovery	4400		Several Hours
Kd51-5	7-6-60	Felton	R. W. Sundstrom	Theis Recovery	5100		Several Hours
Me15-29	2-19-68	Test Well City of Milford	R. W. Sundstrom	Theis Recovery	26		4 Hours
Nc13-3	10-14-70	U.S.G.S. Test Well Greenwood	I. H. Kantrowitz and R. H. Johnston	Theis Recovery	200		12 Hours
Care Cd50	8-6-75	Greensboro Elementary School Greensboro, Maryland	P. P. Leahy and J. F. Williams	Theis non-leaky Artesian	720	1.9×10^{-4}	17 Hours
Care Dd TW-1	5-20-68	Test Well City of Denton, Maryland	P. P. Leahy	Theis non-leaky Artesian	1500	3.6×10^{-4}	3 Hours

Table 3. Continued

WELL NUMBER	DATE OF TEST	NAME AND LOCATION	ANALYSIS BY	METHOD OF ANALYSIS	TRANSMISSIVITY (ft^2/d)	COEFFICIENT OF STORAGE	DURATION OF TEST
			CHESWOLD AQUIFER				
Ic25-10	7-8-74	C. Boggs Cheswold, Delaware	R. D. Varrin	Theis non-leaky	800	5.9×10^{-4}	24 Hours
Jd14-1	1-2-64	Division Street City of Dover	R. W. Sundstrom	Theis Recovery	4385		Several Hours
Jd14-17	5-10-78	Treatment Plant City of Dover	P. P. Leahy	Hantush Modified Leaky Artesian	7400	1.4×10^{-4}	16 Days
Jd15-2	2-17-64	Bayard Avenue City of Dover	R. W. Sundstrom	Theis Recovery	3145		Several Hours
Jd15-4,6[1]	12-30-63	East Dover Elementary School City of Dover	R. W. Sundstrom	Theis non-leaky Drawdown and Recovery	2360	6.2×10^{-4}	Several Hours
Jd25-4,5[1]	3-26-68	Danner Farm City of Dover	R. W. Sundstrom	Theis non-leaky Drawdown and Recovery	1650	3.1×10^{-4}	Several Hours
Jd44-28	11-7-77	Tidewater Utilities Royal Grant Development near Camden-Wyoming, Delaware	P. P. Leahy	Jacob Modified Non-equilibrium	1700		24 Hours

[1] The reported transmissivity represents an average value based on analysis of data collected at both pumping and observation wells.

Table 4. Transmissivity Estimates from Specific Capacities of Wells in Kent County, Delaware

WELL NUMBER	OWNER AND LOCATION	AQUIFER	SPECIFIC CAPACITY [(gal/min) / ft]	DURATION OF TEST	ESTIMATED TRANSMISSIVITY[1] (ft^2/d)	METHOD USED FOR ESTIMATION
Kc31-1	U.S.G.S./D.G.S. Petersburg, Delaware	Piney Point	4.0	12 Hours	2300	Brown
Id32-8	Reichold Chemical Corp. Dover	Cheswold	2.6	1 Day	700	Meyer
Id43-6	Delaware State College Dover	Cheswold	2.0	4 Hours	900	Brown
Id54-8	Towne Point Motel Dover	Cheswold	1.6	52 Hours	666	Brown
Jd14-1	Division Street Well Dover	Cheswold	5.5	38 Hours	2200	Brown
Jd14-2	Power Plant City of Dover	Cheswold	7.9	Several Hours	2300	Meyer
Jd14-6	Water Street City of Dover	Cheswold	16.7	1.5 Hours	5300	Brown
Jd14-7	Farmers Bank City of Dover	Cheswold	10.4	1 Day	2800	Meyer

[1] Storage coefficient is assumed to be 3×10^{-4}.

Table 4. Continued

WELL NUMBER	OWNER AND LOCATION	AQUIFER	SPECIFIC CAPACITY [(gal/min)/ft]	DURATION OF TEST	ESTIMATED TRANSMISSIVITY[1] (ft^2/d)	METHOD USED FOR ESTIMATION
Jd24-1	Dover Street City of Dover	Cheswold	12.0	1 Day	3900	Meyer
Jd35-2	C. Zimmerman near Dover	Cheswold	6.9	1 Day	2000	Meyer
Jd43-2	Camden-Wyoming Water Authority Camden-Wyoming, Del	Cheswold	7.9	12 Hours	3100	Brown
Je14-2	Village Inn Little Creek, Del	Cheswold	2.5	2 Hours	1100	Brown
Je21-2	Kings Cliff Trailor Park Dover	Cheswold	8.8	1 Day	2500	Meyer
Je31-1	Dover Air Force Base Well B	Cheswold	12.6	14 Hours	4550	Brown
Je31-2	Dover Air Force Base Well C	Cheswold	13.6	7 Days	5300	Brown
Je32-3	Dover Air Force Base Well A	Cheswold	5.5	12 Hours	1750	Brown
Je55-1	T. Wilson Kitts Hummock	Cheswold	1.0	16 Hours	400	Brown
Ke12-17	Kent County Magnolia, Delaware	Cheswold	1.0	4 Hours	350	Brown

[1] Storage coefficient is assumed to be 3×10^{-4}.